CLIMATE TREND AND TREELINE DYNAMICS IN NEPAL HIMALAYA

A THESIS SUBMITTED TO THE

CENTRAL DEPARTMENT OF ENVIRONMENTAL SCIENCE

INSTITUTE OF SCIENCE AND TECHNOLOGY

TRIBHUVAN UNIVERSITY

NEPAL

FOR THE AWARD OF

DOCTOR OF PHILOSOPHY

IN ENVIRONMENTAL SCIENCE

BY

NARAYAN PRASAD GAIRE

JANUARY 2016

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RECOMMENDATION

This is to recommend that **Narayan Prasad Gaire** has carried out research entitled "**Climate trend and treeline dynamics in Nepal Himalaya**" for the award of Doctor of Philosophy (Ph.D.) in **Environmental Science** under our supervision. To our knowledge, this work has not been submitted for any other degree.

He has fulfilled all the requirements laid down by the Institute of Science and Technology (IOST), Tribhuvan University, Kirtipur for the submission of the thesis for the award of Ph.D. degree.

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CERTIFICATE OF APPROVAL

On the recommendation of Professor Dr. Madan Koirala, Dr. Dinesh Raj Bhuju and Dr. Marco Carrer, this Ph.D. thesis submitted by Narayan Prasad Gaire entitled "**Climate trend and treeline dynamics in Nepal Himalaya**" is forwarded by Central Department Research Committee (CDRC) to the Dean, IOST, T.U.

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DECLARATION

Thesis entitled “C**limate trend and treeline dynamics in Nepal Himalaya**” which is being submitted to the Central Department of Environmental Science, Institute of Science and Technology (IOST), Tribhuvan University, Nepal for the award of the degree of Doctor of Philosophy (Ph.D.), is a research work carried out by me under the supervision of Professor Dr. Madan Koirala, Central Department of Environmental Science, Tribhuvan University and co-supervision by Academician Dr. Dinesh Raj Bhuju, Nepal Academy of Science and Technology (NAST), Nepal and Associate Professor Dr. Marco Carrer, Padova University, Italy.

This research is original and has not been submitted earlier in part or full in this or any other form to any university or institute, here or elsewhere, for the award of any degree.

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ACKNOWLEDGEMENTS

This work could not been completed successfully without the contribution of various people and organizations since I decided to work in this. I am indebted to Nepal Academy of Science and Technology (NAST) for granting me PhD fellowship and every support to conduct this research including exposure with different national and international organization. This work is a result of a team work. I would like to express my deepest gratitude to my supervisor, Professor Dr Madan Koirala, Central Department of Environmental Science, Tribhuvan University (CDES-TU), for his continuous support, inspiration and guidance throughout this study. I would like to express my deepest gratitude to my co-supervisor, Dr Dinesh Raj Bhuju, Academician, NAST, who has always been a source of inspiration and motivation to me do better and made me proficient. He has guided and supported my research work very closely since the inception of this research work, during field work to the final documentation of the research. I thank my co-supervisor, Dr Marco Carrer, Associate Professor, Padova University, Italy for his support to this work. His support and guidance during data analysis and reporting are highly appreciated. He also taught me dendrochronological tools and techniques during the inception of Dendrochronology Lab in NAST. I am grateful to Dr Santosh Kumar Shah, Scientist, Birbal Sahni Institute of Paleosciences, India, for his continuous support in analyzing and validating my data.

I am indebted to earlier research scholars whose works made this study easy. Furthermore, there are several institutions that directly and indirectly helped to make this research work complete. My special thanks go to Professor Dr Kedar Rijal, head, CDES-TU for his continuous inspirational support in the research. I express my gratitude to the present and former Vice-chancellors, Secretaries, Science Faculty Chiefs, members of PhD unit including Dr. Kanti Shrestha, Iswor Prasad Khanal, Dr Bhoj Raj Pant, Dr Prakash Raut, and Shiva Prasad Upadhayaya for their continuous effort to provide me good research environment. I am indebted to whole NAST family for their continuous support during my study. I am very much indebted to CDES-TU and IOST Dean Office family, TU, for their continuous support and motivation for finishing of this research smoothly. I express sincere gratitude to DNPWC, SNP, MCA and RNP office for giving permission to conduct this work in three protected areas of Nepal. My gratitude is also for DHM for providing the essential climatic data.

Fieldwork of this study is supported by different institutes. NAST provided financial support for MCA and RNP; EvK2CNR provided support for SNP and Pro Natura Fund of Japan via Dr Dinesh Raj Bhuju partially supported for RNP. Various organizations facilitated me to enhance my research capability by supporting me financially and morally to participate in trainings, workshops and conferences. My deepest gratitude and sincere thanks to CDES-TU, EFN-WWFUS, EvK2CNR, Pakistan Council for Science and Technology (PCST) and Federal Urdu University of Arts, Science and Technology (FUUAST), Pakistan; Research Institute for Humanity

and Nature (RIHN), Japan; Institute for Tibetan Plateau Research (ITP) and Third Pole Environment (TPE) Programme and Institute of Geography, Chinese Academy of Sciences, Beijing, China; Birbal Sahni Institute of Paleosciences (BSIP), Lucknow, India; Past Global Changes (PAGES); International Geosphere Biosphere Programme (IGBP); Asia Pacific Network (APN), Japan; Department of Geography of University of Minnesota, USA; Institute of Geography, Friedrich-Alexander University, Erlangen-Nurnberg, Germany. Support from Professor Dr Moinuddin Ahmed, Professor Dr Takeshi Nakatsuka, Professor Dr Achim Bräuning, Dr Masaki Sano, Dr Thorsten Kiefer, Dr Lucien Von-Gunten, Professor Dr Eryuang Liang, Dr Bimala Devkota, Dr Kumar Mainali, Professor Dr Scott Xt. George, Madan Krishna Suwal, Uday Kunwar Thapa, Laxman Pande, Yub Raj Dhakal, Dr Suman Aryal in different stages of this research and publication is highly acknowledged.

Field activities are possible due to the generous support of large number of people and families. I am thankful to the local peoples and hotels of SNP, MCA and RNP who provided food and lodging during my field stay. Ms Prabina Rana provided good guidance as well as support during field work at MCA and SNP. I express my sincere thanks to Dorje Thakuri and family of Prok and villagers of Prok VDC Gorkha, Yeshi Dorje Thakuri, Chimik Hima, Norbu Samden, Norbu Lama, Lakpa, Arbindra Shrestha, Janardan Mainali, Deb Raj Sapkota and NAST's team for their support in field work in MCA; Gajendra Shrestha, Gajendra Tamang, Lakpa Dorje, Nawaraj Nepali, Mahesh Adhikari, Arjun KC, Youba Raj Pokharel in SNP; Ramesh Rokaya, Rup Raj Timilsena and Dinesh Acharya in RNP, and many anonymous persons. My colleagues and friends continuously supported me at various stages of this work. My colleagues and friends Pawan Kumar Neupane and Agni Dhakal are also a source of inspiration to which I often shared my frustrations and happiness during the work at NAST’s lab. All thanks go to my parents, brother, brother in-law, sister, sister in-law, cousins, nieces and other relatives for their continuous inspiration, support, trust, and every investment in my academic endeavors. I would like to dedicate this work to my family who has always supported me to carry out my education and Academician Dr Dinesh Raj Bhuju who conceived idea, dreamed to initiate PhD at NAST and worked tirelessly to fulfill his dream.

Narayan Prasad Gaire

January 2016

ABSTRACT

Nepal boosts good dendroclimatic potential due to diversity in topography, climate, biodiversity, and cultures. Trees at the climatic treeline can act as biomonitors and early warning signals of impacts of climate change on high altitude biota. Based on this fact and considering research gap, a dendroecological and dendroclimatological study was carried out at the treeline ecotones of three high mountain protected areas in Nepal Himalaya: Sagarmatha National Park (SNP), Manaslu Conservation Area (MCA), and Rara National Park (RNP). The study aimed (i) to determine the present position of treeline and associated tree species composition with their structure in Nepal Himalaya, (ii) to develop ring-width chronologies and analyse response of tree growth to the climatic factors, (iii) to assess dynamics of treeline in Nepal Himalaya and find out its underlying climatic factors, and (iv) to reconstruct the past climate of the region. Using vertical belt transects plots (20 m wide and variable length) detail ecological survey and dendrochronologoical study was carried out. Treeline ecotones of the study areas were formed by *Abies spectabilis* D. Don, *Betula utilis* D. Don, *Juniperus recurva, Rhododendron campanulatum* D. Don and *Sorbus microphylla,* with *Salix* sp. at some sites. The position of tree and species limit of the treeline forming *A. spectabilis* and *B. utilis* generally decreased from eastern to western parts of Nepal Himalaya. Regeneration of *A. spectabilis* was better than *B. utilis* in most of the sites. The size parameters such as tree density, diameter at breast height, height, and age of treeline forming *A. spectabilis,* and *B. utilis* decreased with increasing elevation which corresponded with decreasing temperatures. The spatio-temporal population age structure of these species showed both stand densification and upward shifting of the treeline in many sites. The upward shift of *A. spectabilis* during the past ~200 years was calculated as 0.5 to 2.6 m per year. In contrary, *B. utilis* changed very slowly in the past with stabilization in most sites during recent several decades. Climatic response revealed that regeneration of *A. spectabilis* in SNP was positively favored by high average temperature in both winter and summer, in MCA by an above-average monthly maximum temperature during most of the months and above-average precipitation during dry warm summer months, and in RNP by moist and cool year; however, regeneration-climate relationship of *B. utilis* was sometimes weak as well as spatiotemporally different and less conclusive.

Representing each site and species, six ring-width site chronologies dating back up to AD 1763 were developed from *A. spectabilis* and *B. utilis*. Response function analysis revealed that, depending upon the study sites, the radial growth of *A. spectabilis* was limited by temperature and or moisture stress. In SNP region it was more sensitive with summer temperature, while in MCA and RNP region, the growth was more sensitive with spring season temperature and moisture. The radial growth of *B. utilis* was limited mainly due to the moisture stress during spring season with positive relation with precipitation and negative relation with the temperature of the same season; however, in some sites it was due to insufficient temperature during growing period.

The March–June average temperature and total precipitation of western Nepal was reconstructed for past over 170 years (1840-2013 AD), which showed non-significant long-term trend. The temperature reconstruction identified several periods of warming and cooling. The short cold episodes were observed around 1880s, and 1910s, while warm episodes were centered in 1870s, 1890s, and 1980s. Similarly, the reconstructed precipitation showed several wet and dry periods. The correlation between the reconstructed spring temperatures with indexes of sea surface temperature of the equatorial Pacific and extended multivariate ENSO Index revealed a significant negative correlation with monsoon and post monsoons seasons. The relationship with precipitation was in opposite direction than that with temperature. This relationship demonstrates that the climate of western Nepal has spatio-temporal linkages with global scale climatic variability. However, both the observed and reconstructed temperature from MCA region has weak relation with global climatic phenomenon suggesting some local effect in climatic condition.

The different regeneration and migration pattern of studied species indicated that the treelines in Nepal Himalaya were also subject to changes in species composition. Population demography and growth response studies suggested that trees in Nepal Himalaya have a species-specific and site dependent response to climate change. Further studies at treeline ecotone incorporating climatic and non-climatic, biotic and abiotic factors will enhance our understanding on treeline dynamics in Nepal Himalaya in response to the rapid environmental change including climate change.

Key words: Climate change, Dendroecology, Dendroclimatology, Population demography, *Abies spectabilis*, *Betula utilis*, Tree-ring, Treeline, Nepal Himalaya

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%	Percentage
&	and
°	Degree
°C	Degree Celsius
K	Kelvin
p	Probability value
r	Correlation coefficient
R^2	Coefficient of determination
α	alpha
δ	delta

LIST OF ABBREVIATION AND ACRONYMS

°C	Degree Celsius
^{14}C	Carbon 14 isotope
AD	After death of Christ
ARSTAN	Autoregressive Standardization
BC	Before Christ
CAS	Chinese Academy of Sciences
CE	Coefficient of Efficiency
CE	Common Era
cm	Centimeter
CMIP5	Coupled Model Intercomparison Project Phase 5
CO_2	Carbon dioxide
CRU	Climate Research Unit
DB	Diameter at base
DBH	Diameter at breast height
DHM	Department of Hydrology and Meteorology
DNPWC	Department of National Park and Wildlife Conservation
DPL	Dendro Program Library
E	East
e.g.	Example
EFN-WWFUS	Education for Nature, World Wildlife Fund, United States of America
ENSO	El Niño–Southern Oscillation
EPS	Expressed Population Signal
EvK2CNR	Everest K2 and National Research Centre, Italy
et al.	And others
GCA	Gaurisankar Conservation Area
GIS	Geographical Information System
GON	Government of Nepal
GPS	Global Positioning System
HKKH	Hindu Kush Karakoram Himalaya
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Nature Conservation
K	Kelvin

ka	kilo (1000) year
km	Kilometer
km^2	Square kilometer
KNMI	The Royal Netherlands Meteorological Institute
LINTAB	Linear Positioning Table
LNP	Langtang National Park
m	Meter
m asl	Meter above mean sea level
MBNP	Makalu Barun National Park
MCA	Manaslu Conservation Area
mm	Millimeter
N	North
NAPA	National Adaptation Program of Action
NDVI	Normalized Vegetation Index
NP	National Park
NTNC	National Trust for Nature Conservation
NW	North West
O	Oxygen
PDSI	Palmer Drought Severity Index
R	Computer software package
RCP	Representative Concentration Pathway
RE	Reduction of Error
RNP	Rara National Park
S	South
SD	Standard deviation
SE	South East
SNP	Sagarmatha (Mt. Everest) National Park
SNR	Signal-to-Noise Ratio
Sps	Species
SPSS	Statistical Package for Social Sciences
TSAP	Time Series Analysis Programme
UNESCO	United Nations Educational, Social and Cultural Organization
USA	United States of America
VFY	Verify

W	West
yr	Year

CHAPTER 1

1. INTRODUCTION

1.1 Background

Global climate change is a critical issue for the contemporary world. During the period from 1880 to 2012, the globally averaged combined land and ocean surface temperature has increased by 0.85 °C (0.65 to 1.06 °C) (IPCC, 2013), with the most pronounced and rapid changes at high altitudes and latitudes (Diaz & Bradley, 1997; Gobiet et al., 2014; IPCC, 2014). The temperature is projected to rise by 1.4-4.5 ºC by 2100 AD. Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850 (IPCC, 2013). However, there exists spatial and temporal heterogeneity in the past long term temperature trend (Hansen, 2006; Cook et al., 2013; Marcott et al., 2013; PAGES 2k Consortium, 2013; IPCC, 2014; Shi et al., 2015). There is no specific trend in the precipitation; but, inter-annual variability is increasing consistently with many extreme events (IPCC, 2013; Westra et al., 2013). Many physical changes have been attributed to this warming, including sea level rise, melting of glaciers and ice sheets, decreased snow and ice cover, changes in patterns of wind, temperature, and precipitation (summarized in IPCC, 2013, 2014). This rapid climate change has 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 & Yohe, 2003; Root et al., 2003; Walther et al., 2005; Bertin, 2008; Parolo & Rossi, 2008; Chen et al., 2011; Gottfried et al., 2012; Kirdyanov et al., 2012; Pauli et al., 2012; Webb et al., 2012; Telwala et al., 2013; Gaire et al., 2014; IPCC, 2014).

Warming in the Himalaya and adjacent regions is several times greater than the global average (Xu et al., 2009; Shrestha et al., 2012; Telwala et al., 2013). According to projections made by the Intergovernmental Panel on Climate Change (IPCC), average annual warming of the Asian land mass, including the Himalaya, will increase about 3 °C by 2050 and about 5 °C by 2080, with much higher rates toward the Tibetan plateau (Cruz et al., 2007; IPCC, 2007). Similarly, average annual precipitation in this region will increase by 10 to 30% by 2080 (IPCC, 2007, 2014). Several impacts of the climate change in diverse sectors in Himalaya are already been observed (Xu et al., 2009; Shrestha et al., 2012; Bolch et al., 2012; Rai et al., 2013; Telwala et al., 2013; Thakuri et al., 2014). The projected rate of change will further exacerbate the impacts in the various sectors in the Himalaya.

The biophysical consequences of global climate warming strongly urge for development and analysis of climate sensitive biomonitoring systems (Kullman, 2001; IPCC, 2014). Distributing over all life zones, the high mountain biome is the only terrestrial biome where climate-induced changes along all fundamental climatic gradients (altitude, latitude, and longitude) can be compared (Körner, 2012). The high altitude limit of forests, commonly known as treeline, represents one of the most conspicuous vegetation boundaries (Körner, 1998, 2012; Holtmeier, 2009). Körner (1998) defined treeline as the transition zone (ecocline) between the upper limit of the closed montane forest and the tree species line (i.e. the beginning of the treeless alpine zone). Globally occurring treelines can be defined and categorized into four primary forms : 1) Diffuse, characterized by a gradual decrease in height of single-stemmed trees as well as tree density along the treeline ecotone; 2) Abrupt, characterized by a continuous forest >3 m tall directly bordering low alpine vegetation. Tree height as well as density thus changes rapidly; 3) Island, characterized by clumped patches or linear strips (fingers) of krummholz or trees above the continuous forest limit, and 4) Krummholz, characterized by severely stunted or deformed multi-stemmed trees (Harsch and Bader, 2011).

The position of a climatic treeline is mainly due to strong growth limitation by low-temperature conditions (Körner & Paulsen, 2004; Holtmeier, 2009), being worldwide high altitude climatic treelines associated with a seasonal mean ground temperature of 6.7 °C ± 0.8 SD during the growing period (Körner & Paulsen, 2004). Therefore, natural treeline ecotones are taken as sensitive biomonitors and bioindicators of past and recent climate change and variability (Kullman, 1998; Camarero & Guterrez, 2004), and are well-suited for monitoring climate change impact (Becker et al., 2007; Körner, 2012). As most of the high elevation climatic treelines are shaped due to low temperature limitation (Körner & Paulson, 2004; Körner, 2012), treeline is also assumed to represent an ideal early-warning feature that responds structurally, positionally, and physiognomically to climate change particularly to temperature increase (Kullman, 1998, 2001; Holtmeier & Broll, 2005; Kirdyanov et al., 2012;

Körner, 2012). However, the response of treeline to climate change is not unidirectional; it not only varies spatio-temporally but also in relation to treeline form and structure (Holtmeier, 2009; Harsch et al., 2009; Harsch & Badar, 2011).

Treeline is one of the highly studied vegetation ecotones in the world because of its sensitivity towards various environmental changes (Holtmeier, 2009; Körner, 2012). Many dendroecological studies have documented that trees at the treeline often respond to climatic warming with changes in recruitment phase, in tree-density as well as upward advances in the treeline position (Bradley & Jones, 1993; Camarero & Gutiérrez, 2004; Danby & Hik, 2007; Kullman, 2002, 2007; Batllori & Gutiérrez, 2008; Kullman & Öberg, 2009; Leonelli et al., 2011; Liang et al., 2011; Kirdyanov et al., 2012 Mamet & Kershaw, 2012; Oberg & Kullman, 2012; Hofgaard et al., 2013; Aakala et al., 2014). 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 (47%), 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; Harsch & Badar, 2011). Treelines from Tibet and adjacent mountainous regions of China have shifted very little with climate change, however, density of plants is increasing considerably (Wang et al., 2006; Liang et al., 2011; Gou et al., 2012; Lv & Zhang, 2012).

The Himalaya region is very sensitive and vulnerable to climate change impacts, as the rate of change is more pronounced compared to other regions (Shrestha et al., 1999; Shrestha et al., 2012; IPCC, 2013; Qi et al., 2013; Salerno et al., 2015), and vulnerability is exacerbated by fragile young geology and poor economic base (Zurick et al., 2005). Treelines in the Himalaya are mainly formed by the species of the genera *Abies* sps, *Betula utilis*, *Juniperus* sps, *Pinus wallichiana*, *Larix* sps, *Rhododendron campanulatum*, *Sorbus* sps, etc. (Schickhoff, 2005; Miehe et al., 2007; Shrestha et al., 2007; Gaire et al., 2011; Schickhoff et al., 2015); most of them are proven to have dendrochronological potential (Bhattacharyya et al., 1992; Cook et al., 2003; Sano et al., 2005; Dawadi et al., 2013). Therefore, they provide good opportunity to observe changes in community structure as well their response with climate change. However, compared to other mountain systems (Harsch et al., 2009; Harsch & Badar, 2011;

Körner, 2012), very limited research on treeeline of Himalayan mountain range have been carried out, and knowledge gap exists on the relationships of Hindu Kush Karakoram Himalayas (HKKH) treelines to other ecological conditions and processes such as carbon balance, freezing and frost, drought, soil temperature, wind, snow cover, soils, and regeneration (Schickhoff, 2005; Xu et al., 2009; Dutta et al., 2014; Schickhoff et al., 2015). In spite of difficulties in precisely detecting small plot level changes, modeling studies using remote-sensing and repeated photography reported increasing greenery in the treeline ecotone as well as upward shifting of the treeline ecotone at an alarming rate (Panigrahy et al., 2010; Bharti et al., 2012; Singh et al., 2011, 2012, 2013). Similarly, available field based studies have reported an increased tree density with potential upward shifting of the treeline species (Dubey et al., 2003; Bhuju et al., 2010; Gaire et al., 2011; Lv & Zhang, 2012; Chhetri & Cairns, 2015; Schickhoff et al., 2015; Shrestha et al., 2015). There are very limited studies about the climatic factors responsible for treeline formation and dynamics in the Himalaya (Körner, et al., 2012; Liang et al., 2014; Schickhoff et al., 2015). Comparisons of how different species respond to changing climatic conditions give an insight into probable future community composition and the potential formation of novel communities. The dendroecological approach is very useful to calculate the tree establishment rates and to assess response of the forests including treeline to various aspects of environmental changes (Fritts & Swetnam, 1989; Wang et al., 2006; Speer, 2010; Körner, 2012). Hence, this study uses a multiple species approach using dendroecological tools for an assessment of treeline dynamics in central Himalayas.

Information on the long-term trend in the climate including both temperature and hydro-climatic information is very important for evidence-based decision-making, and formulation of appropriate adaptation measures against climate change impacts. The available meteorological data in most parts of Himalayan regions are too short for long term trend analysis and to realistically forecast future trends (Shrestha et al., 1999, 2000; Shrestha et al. 2012). On the other hand, due to diverse topography and graded climate, this region has rich natural archives of multi-proxy climatic sources including tree rings, ice cores, and lake sediments (Bhattacharyya et al., 1992; Fuji & Sakai, 2002; Fujita et al., 2002; Cook et al., 2003; Xu et al., 2010; Nakamura et al., 2012; 2015; Pang et al., 2014). Among these natural archives, tree rings provides high resolution climatic data with highest dating accuracy (Fritts, 1976; Speer, 2010).

There is a climatic gradient from east to west and north to south in the Himalaya, with the eastern part of the Himalaya being relatively moist compared to the western counterpart (Zurick et al., 2005), which is also reflected in sensitivity of the tree species towards climate (Bhattacharyya & Shah, 2009; Shah et al., 2014). Past studies from the HKKH region have reported several promising species for various kinds of dendrochronological studies (Bhattacharyya et al., 1988, 1992, 2006; Ahmed & Sarangzai, 1991; Cook et al., 2003, 2010; Bhattacharyya & Shah, 2009; Ahmed et al., 2011; Gaire et al., 2013). Using this potential, several dendrochronological studies have been carried out. These dendroclimatic studies have reported that, depending upon the location and site conditions, both temperature and moisture stress are limiting factors for the growth of many treeline forming species in the Himalaya (Bhattacharyya & Chaudhary, 2003; Yadav et al., 2004; Sano et al., 2005; Bhattacharyya et al., 2006, Borgaonkar et al., 2011; Gaire et al., 2011, 2014; Lv & Zhang, 2012; Dawadi et al., 2013, Kharal et al., 2014; Liang et al., 2014, Schickhoff et al., 2015). The temperature (Yadav et al., 1997, 1999, 2004; Yadav & Singh, 2002; Shah et al., 2007; Thapa et al., 2014; Krusic et al., 2015; Zafar et al., 2015), precipitation (Singh & Yadav, 2005; Singh et al., 2009; Sano et al 2013; Yadav et al., 2014) and river discharge (Cook et al., 2013; Shah et al., 2013, 2014; Singh & Yadav, 2013) at centennial to millennial scales have also been reconstructed from HKKH region including Nepal. Similarly, a substantial progress is seen in various aspects of dendrochronological studies on the Tibetan plateau and adjacent areas situated in the north of the Himalaya (Yu et al., 2006; Gou et al., 2007; Huang & Zhang, 2007; Liang et al., 2008, 2009, 2011; Zhang et al., 2014). Regional temperature reconstructions have shown spatio-temporal variations in climate (Yadav et al., 1997, 1999, 2004; Yadav & Singh, 2002; Cook et al., 2003; Thapa et al., 2014; Krusic et al., 2015; Zafar et al., 2015) which are consistent to broader regional and global patterns (Cook et al., 2010, 2013; PAGES 2k consortium, 2013; Shi et al., 2015).

The atmospheric temperature in Nepal has been increasing at a rate of 0.04-0.06 °C/year, with a higher rate than the global average (Shrestha et al., 1999; Shrestha & Aryal, 2011; Shrestha et al., 2012; IPCC, 2013; Salerno et al., 2015). There is spatial difference of warming rates with a more pronounced warming trend in the high altitudes of Nepal Himalaya (Shrestha et al., 1999; Shrestha et al., 2012; Kattel & Yao 2013; Salerno et al., 2015). Though no specific trend in precipitation has been observed, extreme events have been increasing in recent years (Shrestha et al., 2000; Shrestha 2008; Kattel & Yao, 2013; Qi et al., 2013). The effect of warming temperature in Nepal Himalaya results in shrinking permafrost areas (Fukui et al., 2007), melting of snow, rapid retreating of glaciers, and formation and expansion of glacial lakes (Fujita et al., 1998; Bajaracharya et al., 2007; Benn et al., 2012; Bolch et al., 2012; Yao et al., 2012; Thakuri et al., 2014), among other phenomena. Impacts on biological processes including phenology, range and distribution shifting of species are also expected but scientific studies on these aspects are scarce (Schickhoff, 2005; Shrestha et al., 2012; Hart et al., 2014). Past works on tree-rings in Nepal have identified several promising species for dendrochronological study including *Abies spectabilis* and *Betula utilis* (Bhattacharyya et al., 1992; Cook et al., 2003; Sano et al., 2005, Dawadi et al., 2013), which can grow up to the treeline ecotone (Schickhoff, 2005; Ghimire et al., 2008). Few dendroclimatic reconstructions can be found from Nepal (Cook et al., 2003; Sano et al., 2005, 2012; Thapa et al., 2014) but are insufficient for generalization of the climatic trend for whole Nepal. Recently, researchers from Nepal and overseas have initiated dendroecological studies covering various treeline sites of Nepal Himalaya (Bhuju et al., 2010; Gaire et al., 2011, 2014; Chhetri & Cairns, 2015; Shrestha et al., 2015; Schickhoff et al., 2015). Preliminary results have shown stable to upward shifting of the treeline ecotone. However, comprehensive studies incorporating multiple species from the diverse topography and sites are still lacking in Nepal, and concrete inferences on the treeline dynamics in response to climate change are yet to be explored.

1.2 Rationale of the study

The high altitude regions of Nepal Himalaya are severely affected by the impacts of climate change; however, the available meteorological data are too short for long term trend analysis and realistically forecast future. To fill this data gaps there are prospects of using other multi proxy climatic data including tree-rings. Nepal hosts several tree species with already proven dendrochronological potential. But only four climatic reconstructions are present till date, and which are too few and incomprehensive to capture the geographical heterogeneity of the country and for evidenced based decision making. This makes further dendroclimatic studies imperative.

It is a well-established fact that treelines act as bioindicator and biomonitor of the past climate change and variability in high elevation areas. Nepal Himalaya provides an excellent opportunity for various aspects of treeline research due to its diverse mountainous topography and strong climatic gradients. However, vast knowledge gaps exist in this aspect because very few researches with limited scope have been carried out. It is commonly reported that the elevation of the treeline position in Nepal Himalaya generally decrease while moving from east to west (Schickhoff, 2005), yet we do not have the exact geo-referenced position and species composition, which is the fundamental basis for the long term monitoring of the treeline dynamics in response to climate and other environmental changes. Studies from the treeline ecotone of the Nepal Himalaya are rather few in numbers, incomprehensive and limited in scope mainly focusing regeneration dynamics of single species from a site rather than the climatic response of regeneration, treeline dynamics and their climatic response. This situation demands for further comprehensive study in the treeline areas of the country.

Sagarmatha National Park (SNP), a natural world heritage site and an ecological entity in the highest elevation of the world, offers opportunities for multiple aspects of research in a natural laboratory (Jha, 2010). The park is vulnerable to climate change as it already experienced rapidly increasing temperature but weakening precipitation (Qi et al., 2013; Salerno et al, 2015). The known impacts of this changing climate in the SNP area have evidenced from the shrinkage of permafrost area (Fukui et al., 2007), melting of snow, rapid retreating of glaciers, and formation and expansion of glacial lakes (Benn et al., 2012; Bolch et al., 2012; Thakuri et al., 2014). The landscape of the area is under constant modification since Sherpa people started to inhabit the area since over 500 years ago, and rapidly increasing tourism and climate change has elevated the pressure in the area (Byers, 2005; Garbarino et al., 2014). Impacts of this environmental change on forest and biodiversity is also expected, however, among the over 1000 studies carried out in the area, very few studies have focused in this aspect (Bhuju et al., 2010; Ferrarini et al., 2014; Garbarino et al., 2014; EvK2CNR, 2014). Moreover, no studies have been carried out incorporating the response of multiple species of the treeline area to environmental (climate) change.

Manaslu Conservation Area (MCA) in central Nepal is one of the least explored protected areas; so very few scientific studies from the MCA can be found dealing with the forest and biodiversity (Shrestha et al., 2012; Sujakhu et al., 2013; Mainali et al., 2015). The area is very remote and inaccessible having many locations without the direct influence of anthropogenic activities. Hence, MCA is an appropriate place to study the impact of climate change and also to establish reference baseline studies for long term monitoring.

Rara National Park (RNP), situated in mid-western Nepal, is biologically and ecologically significant protected area. Due to the remoteness of the area, very few scientific studies mainly focusing on the environment of Rara Lake have been carried out (Suzuki, 1990; Nakamura et al., 2012, 2015). Nevertheless, studies about the impacts of climate change in forest and biodiversity of the region are limited. But, due to the relocation of human settlement from the RNP during its establishment, it provides an opportunity to study the influence of both land use and climate change in its natural environment.

Realizing these research gaps, this study was undertaken to record geo-referenced species composition and treeline position in Nepal Himalaya. As there are projected impacts in physical environment and biological communities, the treeline ecotone could be an important location to monitor impacts of climate change. This study focuses on multiple treeline sites with different environmental conditions and some specific species are used to explore any advancement in the treeline in different environmental gradients. It is envisaged that the response of multiple species to climate change will enable us to develop appropriate adaptation and conservation measures to protect high elevation species from the adverse impacts of climate change. The growth-climate and regeneration-climate response of multiple species from multiple sites provide a science-based perspective about the future treeline position and formation of the probable novel community.

Nepal is very vulnerable to the impacts of climate change because the rate of warming is higher as in other regions, and its vulnerability to climate change is compounded by its fragile topography and poor resilience due to weak economic condition. On the other hand, there is lack of long instrumental climatic data for long-term trend analysis, realistically forecast future change, and develop suitable adaptation measures to cope with adverse impacts of this climate change. This study aims to reconstruct climatic history of the study region. The Government of Nepal has prepared National Adaptation Program of Action (NAPA) to cope with the possible adverse impact of climate change, in which the biodiversity sector in one of the important themes (GON, 2010). It is very essential to know how particular species are responding to various dimensions of environmental change, particularly climate change, before the development of suitable adaptation or conservation measures (e.g. ecosystem based adaptation measures). This present study tries to fulfill the data gap in this respect too. The findings of the study will be useful to academia, policy makers, planners and local peoples.

This study is concentrated to answer the following research questions:

- Where is the exact position of the treeline ecotone in different parts of the Nepal Himalaya and how is the respective species composition?
- Is there any change in the treeline position in Nepal Himalaya? If yes, which factor is most responsible for the dynamism of the treeline ecotone?
- What is the response of various tree species at treeline to climatic variables, mainly with temperature and precipitation?
- What is the climatic history of the region?

1.3 Objective of the study

The broad objective of the study is to assess the climate trend and treeline dynamics in Nepal Himalaya

The specific objectives of the study include:

1. To determine the present position of treeline and associated tree species composition with their structure in selected sites of Nepal Himalaya
2. To develop ring-width chronologies and analyze response of tree growth to the climatic factors
3. To assess dynamics of treeline in Nepal Himalaya and find its most responsible (climatic) factors, and
4. To reconstruct the past climate of the region

1.4 Hypotheses

Consistent to the observations in the other parts of the world, the growth of trees at treeline in Nepal Himalaya might directly respond to temperature because it is very cold environment. Therefore, the limiting factor for tree growth in such areas would be mean temperature before and during the growing season.

Null Hypothesis: The tree growth at treeline does not have any relationships with climate.

Alternative Hypothesis: At an altitudinal treeline limit, the tree growth is positively correlated with temperature, i.e. the limiting factor for growth is temperature. In contrast, in dry areas available moisture is the limiting growth factor.

Since temperature is the main limiting growth factor at treeline, position of the treeline is changing with increasing temperature. Diffuse treelines are more likely to advance than abrupt or krummholz treelines. We speculate that diffuse treelines may be strongly limited by growing season temperatures and hence particularly responsive to overall temperature increases. We hypothesized that the upslope movement of diffuse treelines in the Nepal Himalaya are expected to be proportional to both winter and summer warming as reported by Harsch et al. (2009), and that trees would be expected to grow more dense in response to warming.

Null Hypothesis: Treeline position and stand structure are independent from climate change.

Alternative Hypothesis: Treeline position and stand structure are changing with climate change in the study area.

CHAPTER 2

2. LITERATURE REVIEW

Mainly three aspects of the studies are relevant within the scope of present study. These include climate change and its impacts, treeline in context of global change, and dendrochronological research in context of climate change and its impacts studies. Hence, the relevant literature dealing with these aspects is reviewed in following sub-chapters.

2.1 Climate change and its impacts

The climate of the earth is constantly changing since its evolution. However, the earth's climate is changed rapidly after the industrial revolution mainly due to anthropogenic activities. The globally averaged combined land and ocean surface temperature data show a warming of 0.85 °C over the period 1880 to 2012 (IPCC, 2013). The temperature change in high altitude or latitude is more pronounced as compared to other regions (Diaz & Bradley, 1997, 2003; IPCC, 2013). In addition to multi-decadal warming, global mean surface temperature exhibits substantial decadal and interannual variability. However, there are spatial and temporal variations in long-term temperature and precipitation change (Mann et al., 2009; PAGES 2k Consortium, 2013).

Modeling studies have projected to rise in temperature by 1.5~4.8 °C in the twenty-first century (IPCC, 2013) in a doubling of the atmospheric CO_2 concentration. According to IPCC (2013), global surface temperature change for the end of the 21st century will likely exceed 1.5 °C relative to 1850 to 1900 for all RCP scenarios except RCP2.6. Similarly, increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to likely be in the ranges derived from the concentration-driven CMIP5 model simulations, that is, 0.3 °C to 1.7 °C (RCP2.6), 1.1 °C to 2.6 °C (RCP4.5), 1.4 °C to 3.1 °C (RCP6.0), 2.6 °C to 4.8 °C (RCP8.5) (IPCC, 2013). Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform (IPCC, 2013).

Looking at the regional scale, warming trends and increasing temperature extremes have been observed across most of the Asian region over the past century (IPCC, 2014). According to IPCC (2014), the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale. Precipitation trends have shown a strong variability, with both increasing and decreasing trends observed in different parts and seasons of Asia, however extremes events are increasing (IPCC, 2014). Modeling studies revealed that the warming is very likely in the 21st century for all land areas of Asia in the mid- and late-21st century, based on the CMIP5 simulations under all four RCP scenarios (IPCC, 2014). Ensemble-mean changes in mean annual temperature exceed 2 °C above the late-20th century baseline over most land areas in the mid-21st century under RCP8.5, and range from greater than 3°C over South and Southeast Asia to greater than 6 °C over the high latitudes in the late-21st century (IPCC, 2014). Projections of future annual precipitation change revealed that precipitation increases are very likely at higher latitudes by the mid-21st century under the RCP8.5 scenario, and over eastern and southern areas by the late-21st century (IPCC, 2014). Under the RCP2.6 scenario, increases are likely at high latitudes by the mid-21st century, while it is likely that changes at low latitudes will not substantially exceed natural variability (IPCC, 2014). Future increases in precipitation extremes related to changes in the Asian summer monsoon dynamics are very likely in East, South and Southeast Asia (IPCC, 2014). More than 85% of CMIP5 models show an increase in mean precipitation in the East Asian summer monsoons, while more than 95% of models project an increase in heavy precipitation events. All models and all scenarios project an increase in both the mean and extreme precipitation in the Indian summer monsoon (IPCC, 2014).

There is no specific trend in precipitation change averaged over global land areas (IPCC, 2013). Averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has increased since 1901 while for other latitudes there is a positive or negative trend (IPCC, 2013). However, changes in many extreme weather and climate events have been observed since about 1950 (IPCC, 2013; Westra et al., 2013). Most land regions will receive more precipitation than earlier. A recent study of annual maximum daily precipitation time series using a global dataset of 8326 high-quality land-based observing stations with more than 30 years of record over the period from 1900 to 2009 revealed a statistically significant increasing trends in extreme precipitation at the global scale (Westra et al., 2013).

Available studies from the Himalayas, Indian subcontinent and Tibetan plateau and adjacent areas have shown a rapid temperature increase which is commonly attributed to anthropogenically increased greenhouse gas concentrations (Fan et al., 2011; Shrestha et al., 2012; Yang et al., 2013). The climate change in the Himalayan region is more pronounced as compared to the other regions (IPCC, 2013). Data from the HKKH region not only have shown a linear trend in the climatic variable, but also an increase in the extreme climatic events like drought, floods, etc. (Shrestha et al., 1999; Krishnamurthy, 2009; Shrestha et al., 2012; del Rìo et al., 2013; Panday, 2014; Sheikh, 2015). Telwala et al. (2013), compared to the last two centuries, observed evidence of warmer winters in the Sikkim region of eastern Himalaya with an increase in mean temperatures of the warmest and the coldest months by 0.76 ± 0.25 °C and 3.65 ± 2 °C, respectively. Time series of seasonal precipitation from the region had shown a consistent measurement of interannual variability for the HKKH, with a decreasing trend in Himalaya during summer and no any specific trends in Hindu-Kush Karakoram during winter (Palazzi, 2013). The projection of precipitation under two different future scenarios (RCP 4.5 and RCP 8.5) reveals an increasing trend over the Himalaya during summer, associated with an increase in wet extremes and daily intensity, and a decrease in the number of rainy days. The model projections using A1B emissions scenario for the period from 1961 to 2098 AD indicate that significant warming will occur throughout the HKKH region toward the end of the 21st century (Kulkarni et al., 2013). Summer monsoon precipitation is expected to be 20–40% higher in 2071–2098 AD than it was in the baseline period (1961–1990 AD) (Kulkarni et al., 2013).

Available meteorological data have shown a rapid increase in average annual maximum and mean temperatures in Nepal by a rate of 0.04 to 0.06 °C/yr (Shrestha et al., 1999, Shrestha & Aryal, 2011; Shrestha et al., 2012). There exists spatial heterogeneity in this temperature trend with high elevation areas are getting more warmer compared to low elevation regions (Shrestha et al., 1999; Shrestha & Aryal, 2011; Shrestha et al., 2012). By analyzing temperature and rainfall data from the entire Himalayan region, Shrestha et al. (2012) reported a significant change in temperature and rainfall across the Himalayas between 1982 and 2006 AD. The average annual mean temperature during the 25 year period has increased by 1.5 ºC with an average increase of 0.06 ºC/yr while average annual precipitation has increased by 163 mm or 6.52 mm/yr (Shrestha et al., 2012). Another study of the temperature trend (1980-2009) using 13 stations situated in the mountainous region across Nepal has shown an increase in average temperature (0.38 ºC/decade) with higher increment rates of maximum temperature (0.65 ºC/decade) and slight increasing (0.11 ºC/decade) but with high interannual variability in minimum temperature (Kattel & Yao, 2013). From an analysis of the minimum, maximum and mean temperature and precipitation time series derived from seven stations located on the southern slopes (between 2660 and 5600 m asl) of Mt. Everest over the last twenty years (1994–2013 AD), Salerno et al. (2015) revealed that the main and more significant increase in temperature is concentrated outside of the monsoon period. At higher elevations of the Everest region, minimum temperature (0.072 ± 0.011 °C/yr) increase is higher than maximum temperature (0.009 ± 0.012 °C/yr), while mean temperature increased by 0.044 ± 0.008 °C/yr (Salerno et al., 2015). There is not any consistent trend in the precipitation change in Nepal (Shrestha et al., 2000; Ichiyanagi et al., 2007; Qi et al., 2013; Salerno et al., 2015). Many areas are receiving more precipitation than during earlier periods while some are receiving less precipitation. Salerno et al. (2015) observed a substantial precipitation weakening (9.3 ± 1.8 mm/yr) during the monsoon season in the southern part of Everest region. Similarly, based on data from 10 meteorological stations on the southern slope of the Mt. Everest region in Nepal between 1971 and 2009 AD, Qi et al. (2013) analyzed the spatial and temporal characteristics of climatic change in the region. The results showed that, between 1971 and 2009, the rising rate of annual mean temperature was 0.25 °C/decade, a value which is highly influenced by maximum temperature increase. In 1974 and 1992, the temperature rose noticeably in February and September in the southern region when the increment passed 0.9 °C (Qi et al., 2013). In this region, precipitation showed an increasing trend of 4.27 mm/yr though not statistically significant, but there was an increase in extreme precipitation events (Qi et al., 2013). A modeling study using different climate circulation models considering various IPCC projected scenarios have shown a rapid increase in temperature on different temporal scales in the 21st century while precipitation patterns are inconsistent (Agarwal et al., 2015). However, the available meteorological data from the Nepal Himalaya are inadequate for a reliable forecast of future trend considering low frequency signals (decadal to centennial scales) in the climatic data, demanding further studies using other proxy climatic sources like tree rings, ice cores, lake sediments, etc.

This rapidly changing climate has several biophysical impacts (IPCC, 2014). In many regions, changing precipitation or melting snow and ice are altering hydrological systems (IPCC, 2014). Climate change is causing retreating of glaciers, permafrost warming and thawing in high latitude regions and in high-elevation regions (IPCC, 2014). Many terrestrial, freshwater, and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances, and species interactions in response to ongoing climate change (Parmesan and Yohe, 2003; Root et al., 2003; Parolo and Rossi, 2008; Chen et al., 2011; Gottfried et al., 2012; Kirdyanov et al., 2012; Pauli et al., 2012; Webb et al., 2012; IPCC, 2014). In the Himalayas, different impacts of climate have been reported from various sectors including forest and biodiversity (Xu et al 2009; Telwala et al., 2013; IPCC, 2014). The changes in temperature and precipitation immediately reflect themselves as changes in phenology of local vegetation types. Shrestha et al. (2012) examined phenological changes in all major ecoregions of the Himalayas. During 1982 and 2006 AD, the average start of the growing season has advanced by 4.7 days or 0.19 days/yr and the length of growing season appears to have advanced by 4.7 days or 0.19 days/yr, but there has been no change in the end of the growing season (Shrestha et al., 2012). There is substantial spatial and seasonal variation in changes in climate and phenological parameters across the Himalayas (Shrestha et al., 2012). Telwala et al. (2013) found range and distribution shifts of many species in response to climate change in the eastern Himalaya. Telwala et al. (2013) recorded warming-driven geographical range shifts in 87% of 124 endemic plant species in Sikkim region; upper range extensions of species have resulted in increased species richness in the upper alpine zone, compared to the 19th century. The study recorded a shift of 23–998 m in species' upper elevation limit and a mean upward displacement rate of 27.53 ± 22.04 m/decade (Telwala et al., 2013). The plant assemblages and community structure in the Himalaya is substantially and continuously changing due to the impact of warming (Telwala et al., 2013). The continued trend of warming is likely to result in ongoing elevational range contractions and eventually, species extinctions, particularly at mountaintops (Telwala et al., 2013). To assess the impacts of the climate change in the high mountain area we have to find out some indicator place or species, in this regards the treeline ecotone could be very suitable area.

2.2 Treeline

2.2.1 Introduction

The treeline represents one of the most obvious vegetation boundaries in the high elevation or latitude. Körner (1998) defined treeline as the transition zone (ecocline) between the upper limit of the closed montane forest and the tree species line (i.e. the beginning of the treeless alpine zone). The upper treeline represents the upper elevational limit of forest and tree growth on high mountains due to environmental constraints such as cold temperatures, drought, low nutrient availability, water logging, and stormy winds, etc. (Holtmeier, 2009; Körner, 2012). Körner (1998) mentioned that in reality, the transition from uppermost closed montane forests to the treeless alpine vegetation is not a line, but a steep gradient of increasing stand fragmentation and stuntedness, often called the treeline ecotone. Armand (1992) stated that any natural boundary is in reality a transition zone, which has its own two boundaries. "Kampfzone" is another term for the upper timberline belt in recognizing the severe growth conditions that trees must face at their upper elevational limit (Wieser & Tausz, 2007). Transitions differ depending on the dominant environmental driver, the structural and physiological causes for such life form.

On the basis of position and causes of treeline formation, different types or terminologies to represent the treeline have been used for example: Climatic treeline, Polar treeline, Inverted treeline, Continental treeline, Maritime treeline, Historic treeline, Potential treeline, Orographic treeline, Edaphic treeline, Anthropogenic treeline, Actual treeline, and so on (Holtmeier, 2009). Harsch and Bader (2011) recognized four globally occurring primary forms of treelines: 1) Diffuse, characterized by a gradual decrease in height of single-stemmed trees as well as tree density along the treeline ecotone; 2) Abrupt, characterized by a continuous forest >3 m tall directly bordering low alpine vegetation. Tree height as well as density thus changes rapidly; 3) Island, characterized by clumped patches or linear strips (fingers) of krummholz or trees above the continuous forest limit, and 4) Krummholz, characterized by severely stunted or deformed multi-stemmed trees. The term krummholz represents environmentally dwarfed forms of tree species that become upright in favorable sites, the term scrub is applied to those timberlines species whose shrubby form is of genetic origin (Wardle, 1974; Tranquillini, 1979; Holtmeier, 2003).

All researchers working in the treeline areas have defined a certain minimum height to define a tree. However, there is not uniformity in the minimum height, which ranges from two to eight meter; the usages of which varies among the authors, regions of study, and species being studied (Holtmeier, 2009). It is useful to define the tree limit as the upper limit of trees, krummholz and shrubs higher than 2 m (Wardle, 1974), which is also a commonly accepted height criterion in the treeline research in Nepal (Gaire et al., 2011, 2014; Chhetri & Cairns, 2015; Shrestha et al., 2015).

Treeline is possibly the best known and most studied of all distribution boundaries of trees (Holtmeier, 2009; Körner, 2012). A large number of authors have described the worldwide positions of treelines (e.g. Troll, 1973; Wardle, 1974; Baumgartner, 1980; Arno, 1984, Körner, 1998; Miehe et al., 2007). Rochefort et al. (1994) have provided an overview in historical trends. Ohsawa (1990) and Leuschner (1996) have reviewed works from tropical and subtropical mountains. Schickhoff (2005) has given an overview of the current state of the treeline research in the HKKH region. Most of the studies considered latitude as a surrogate of temperatures. In both hemispheres, the upper treeline rises from high latitudes towards the subtropics, and then gradually declines in the tropical equatorial zone (Weiser & Tausz, 2007; Miehe et al., 2007; Körner, 1998, 2012). From a linear regression of the treeline altitude/latitude relationship in the northern hemisphere, Körner (1998) found a change in treeline altitude of 75 m per degree of latitude between 70° and 45° N, and over the whole temperate-subtropical transition (50 ± 30° N) the slope is 130 m per degree of latitude. The altitudes of treelines depend not only on latitudes but also on continentality, especially in temperate interior zones of North America and Asia, where treelines are nearly as high as those of the tropics (Schickhoff, 2005; Weiser & Tausz, 2007).

The highest treeline in the northern hemisphere is of *Juniperus tibetica* Kom which is found at 4900 m asl in southeast Tibet (29°42' N, 96°45' E) and the highest tree stands of *Juniperus indica* Bertol. in the Himalaya were found in northern Bhutan at 4750 m asl (Miehe et al., 2007). Tree species growing at treeline varies across the region and major tree genera of treeline ecotone include summer green species like *Larix, Betula, Nothofagus*, etc and evergreen species like *Picea, Pinus, Abies, Juniperus, Araucaria, Podocarpus, Eucalyptus,* etc. (Miehe et al., 2007; Holtmerier, 2009; Körner, 2012).

Schickhoff (2005) provided an extensive overview on the treeline research from the HKKH region. Upper timberline elevations in the HKKH region increase along two gradients: a NW-SE gradient corresponding to higher temperature sums at same elevations along the mountain arc. A second gradient is developed in peripheral-central direction from the Himalayan south slope to the Great Himalayan range and the Tibetan highlands. Increasing timberline elevations along this gradient are related to the combined effects of continentality and mass-elevation, both leading to higher temperature sums (Schickhoff, 2005). Potentially natural timberline elevations are higher at south-facing slopes compared to north-facing slopes. With regard to physiognomy, high coniferous forests give way to medium-sized broadleaved tree stands and finally to a krummholz belt (Schickhoff, 2005). This is the dominant timberline pattern on shady slopes, whereas remnant open coniferous forest stands on sunny slopes dissolve into isolated patches or single crippled trees higher up (Schickhoff, 2005). Along the NW-SE gradient, north-facing slopes show a floristic change from deciduous *Betula*- to evergreen *Rhododendron*-dominated upper timberlines, which must be attributed to decreasing winter cold and strongly increasing humidity levels. *Juniperus* spp. are the principal timberline tree species on south-facing slopes throughout the mountain system in the HKKH regions (Schickhoff, 2005).

The treeline position and dynamics is the result of interactions of several biotic and abiotic factors. Although, on a global scale, the upper limit of different tree species may vary with respect to site conditions, the upper limit is ultimately dependent on heat balance, which everywhere becomes increasingly unfavorable with rising elevation (Körner & Paulsen, 2004; Wieser & Tausz, 2007). Despite the evident relatedness of tree life limitation at high altitude to temperature, the physiological mechanisms involved are still under debate and a multitude of factors, acting singly or in combination have been proposed to be responsible for the upper elevational limit of tree life (Holtmeier, 2009).

In more than 200 years of research on treeline phenomena worldwide, several hypotheses have been proposed to explain the responsible factors for the upper elevational limit of tree life (Körner, 1998, 2012; Wieser & Tausz, 2007; Li et al., 2008). Four environmental hypotheses and two biological hypotheses have been suggested for interpreting the alpine treeline formation (Körner, 1998, 2012; Li et al., 2008). These include: (1) Climatic stress as a result of repeated damage by freezing, frost desiccation and phototoxic effects; Frost damage may also be a contributing factor to tree life limit at high elevations, (2) Disturbance due to mechanical damage by wind, ice blasting, snow break and avalanches; (3) Insufficient tissue maturation because of the short growing season; (4) Temperature-limited reproduction, (5) Direct growth limitation, and (6) Carbon limitation. The first four hypotheses are related to the alpine/arctic physical environment (physical hypotheses), related to local site conditions and are limited to local treeline phenomena and cannot be applied on a global scale (Li et al., 2008). Only the biological hypotheses, that is, the carbon/source limitation hypothesis or the growth/sink limitation hypothesis may be used to explain the functional mechanism of global alpine/arctic treeline formation (Körner, 1998, 2012; Li et al., 2008). Li et al. (2008) reported that nitrogen does not limit the growth and development of trees at the Himalayan treelines and the treeline did not show consistent evidence of source/carbon limitation or sink/growth limitation in treeline trees. However, treeline trees may suffer from a winter carbon shortage.

According to Körner and Paulsen (2004), disregarding taxon-, landuse- or fire-driven tree limits, high elevation climatic treelines are associated with a seasonal mean ground temperature of 6.7 °C (±0.8 SD; 2.2 K amplitude of means) for different climatic zones. Temperatures are higher (7–8 °C) in the temperate and Mediterranean zone treelines, and are lower in equatorial treelines (5–6 °C) and in the subarctic and boreal zone (6–7 °C). There are genus-specific boundaries rather than boundaries of the life-form tree (Körner, 1998, 2012). Soil temperatures are associated with physiognomic transitions, treeline position, and spatial regeneration patterns in treeline ecotone of the Rolwaling valley, Nepal (Schwab et al., 2015). They measured a growing season mean soil temperature of 7.5 ± 0.5°C, which is higher than the global average (Körner, 2012). As temperature is widely considered to be the primary control on treeline formation and maintenance of altitudinal and polar treelines with global relationships between treeline position and temperature isotherms (Körner &

Paulsen, 2004), fluctuations in treeline position in accordance with past temperature changes (Lloyd & Graumlich, 1997), global warming is expected to cause treelines, to advance to higher elevations and more northerly latitudes. Therefore, treeline position is widely thought to be temperature sensitive and potentially responsive to climate warming (Holtmeier & Broll, 2005), and it is taken as an important indicator of environmental change, particularly global warming (Kullman 2001, 2002).

The sensitivity of treelines to environmental change infers a certain state of readiness of the trees to respond to changing conditions which can take place by changes in growth, growth forms, regeneration and treeline structures (spatial structures, mosaics), and can also be related to changes in alpine or tundra vegetation, age classes and distribution pattern of plant communities (Holtmeier & Broll, 2005; Holtmeier, 2009). The treeline is a space- and time-related phenomenon. Short-term response, defined as a year or less, is reflected in individual trees. Medium-term response (some years to a few decades) is mirrored in changing tree physiognomy (phenotypical response), tree-ring width and density, survival rate in seedlings and young trees, successional stage of the plant cover, etc. (Holtmeier & Broll, 2005). Medium-term and long-term responses (several decades to one hundred or more years) may be simulated by scenarios based on the projection of the present empirical relationships between treeline and environmental factors into a warmer future environment (Holtmeier & Broll, 2005). However, the sensitivity of treelines to environmental change, and in particular, to climate warming, varies with local and regional topographical conditions and thus differs as to its extent, intensity and the process of change (Holtmeier & Broll, 2005).

In cases where orographic factors prevent forest establishment, warmer climate will not cause an advance to a greater elevation as long as mass wasting, debris slides, etc., occur (Holtmeier & Broll, 2005). Moreover, temperature may not be the dominant factor controlling treeline position at some sites because the direct influence of temperature may be masked by interactions with other factors such as precipitation, cold-induced photoinhibition (Danby & Hik, 2007), disturbance (Lescop-Sinclair & Payette, 1995; Speed 2010, 2011) or plant–plant interactions (Bekker, 2005).

2.2.2 Treeline research in the frontiers of climate change

Treeline ecotone has attracted the attention of scientists throughout the world since long time. A global meta-analysis study (Harsch et al., 2009) indicated that, regardless of form, location and degree of temperature change experienced over the last century, treeline positions have either advanced or remained stable. Treelines had advanced since 1900 AD at 87 out of 166 sites (52%) (Harsch et al., 2009). Of the sites that showed no advance, 77 had remained stable whereas two sites that had experienced disturbance were receded. Looking at the areas covered by the treeline studies, most of the studies have been found in the Northern Hemisphere (Harsch et al., 2009). While looking at the continent wise study, treeline of mountain in North America and Europe have been studied more extensively as compared to the South America, Asia and Africa.

The prevailing view is that high altitude and latitude treelines are controlled by summer temperatures (Holtmeier & Broll, 2007; Gehrig-Fasel et al., 2008; MacDonald et al., 2008), with treeline position over much of the globe coinciding with a mean growing season temperature of 5–6 °C (Körner & Paulsen, 2004). However, Harsch et al. (2009) did not find a clear association between probability of treeline advance and rate of mean annual or summer temperature increase. For example, of the 111 sites in which annual temperature had increased over the study duration, 63 (57%) had advanced, and of the 55 sites that had cooled, 24 (44%) had advanced. Treelines that had warmed during the winter months were more likely to advance and the diffuse treelines are more likely to advance than other form (Harsch et al., 2009).

Different treeline forms show their own pattern of response with climate change. Diffuse forms that can be found in both alpine and arctic treelines are most frequently studied form on a global scale (Harsch & Bader, 2011). If diffuse treelines are limited primarily by growth, then diffuse treelines are more likely to be in equilibrium with growing season temperature and exhibit greater sensitivity to changes in minimum growing season temperature than the other treeline forms. Diffuse treelines have exhibited an earlier, stronger response signal than the other treeline forms; over 80% of diffuse treelines worldwide are advancing compared with 22% of abrupt, island or krummholz treelines (Harsch & Bader, 2011). The advance in diffuse treelines initiated 10-40 years earlier than other treeline form (Harsch & Bader, 2011). Advance has been less commonly observed in krummholz than in diffuse treelines. Krummholz form is commonly attributed to damage associated with factors such as wind abrasion, snow and ice damage. Hence, advance in krummholz and abrupt treelines may occur only when winter warming is sufficient to ameliorate other constraints, or when temperatures increase sufficiently to compensate for those constraints for radial growth and regeneration (Harsch et al., 2009; Harsch & Badar, 2011).

Disturbance legacies may influence treeline position and its ability to respond to climate changes. Past disturbances can shape treeline structure and influence initial recruitment patterns but subsequent patterns of recruitment and spread may be more strongly controlled by climate (Holtmeier & Broll, 2005; Vittoz et al., 2008). Interannual variation can have a significant effect on treeline advance (Camarero & Gutiérrez, 2004). Recruitment and survival are both highly sensitive to short periods' markedly cooler or warmer than the general temperature trend. Until the general warming trend consistently exceeds interannual variability, treeline advance may depend upon the coincidence of favourable conditions over sufficient years to permit establishment, growth and survival (Szeicz & MacDonald, 1995; Wang et al., 2006; Harsch et al., 2009).

Though treelines are considered thermally limited and average temperatures have increased globally over the last century, treeline advance is not a worldwide phenomenon (Holtmeier & Broll, 2007; Harsch et al., 2009) or treeline advance is not universal. Only few studies have explicitly mentioned about the treeline advance rate with climate change, in spite of other large number of studies reported the upward advancement of treeline and/or species limit (Harsch et al., 2009). Here, an attempt is made to review those studies which mentioned about the rate of upward shifting of treeline. The rate of upward as well as poleward shifting of treeline or upper distribution limit ranged from 0.02 to 7.5 m/yr in the different region of the world (Harsch et al., 2009 and references therein). Though there are wide discrepancies in the reporting in the shifting, the rate of treeline shifting in the Himalaya (1.4-3.4 m/yr) is compatible with the rate of the shifting in the Alps and Scandes mountains. Swedish Scandes is the most studied area followed by Alps, White Mountain and

Himalaya. Some studies reported 100 m/decade lateral migration of some tree species. Looking at the species reported, *Abies spectabilis, Abies georgei, Abies lasciocarpa*, *Betula pubescens*, *Betula utilis*, *Larix deciduas*, *Picea abies*, *Picea engelmannii*, *Pinus contorta*, *Pinus sylvestris*, *Pinus uncinata*, *Pinus wallichiana*, are common. Studies not only reported the treeline advance but also in-growth of forests and stand densification in the treeline ecotone as well as increased regeneration in different regions of the world (eg. Kullman 2001, 2002, 2007; Camarero & Gutiérrez, 2004; Danby & Hik, 2007; Gehrig-Fasel et al., 2007; Harsch et al., 2009; Batllori & Gutiérrez, 2008; Vittoz et al., 2008; Kullman & Öberg, 2009; Chauchard et al., 2010; Leonelli et al., 2011; Mamet & Kershaw, 2012; Kirdyanov et al., 2012). We have to consider the fact that increased temperature is one of the important factors among the several factors contributing the formation and dynamics of the treeline in the different location of the globe. The differential regeneration and migration of various tree species with climate change can transform the community structure and composition at the treeline and can have various consequences.

Lescop-Sinclair and Payette (1995) found displacement of the longitudinal position of the black spruce (*Picea nlariana* (Mill.) B.S.P.) treeline of about 12 km towards Hudson Bay, Canada since the late 1800s, most likely as a result of recent warming.

Cuevas (2002) found an episodic regeneration of *Nothofagus pumilio* in cycles of a length of 7–8 years to those for seed production across an altitudinal gradient in Tierra del Fuego, Chile. Individuals at the altitudinal treeline had an average age of 160 years in 1996, suggesting that the border has remained static for at least a century and a half.

Kullman (2002) found that since the early 1950s, the range-margins of *Betula pubescens* ssp. *Tortuosa* (mountain birch), *Picea abies* (Norway spruce), and *Pinus sylvestris* (Scots pine), *Sorbus aucuparia* (rowan) and *Salix* spp. (willows) have advanced by 120–375 m to colonize moderate snow-bed communities. Similarly, tree limit has been rising by 100–150 m in the same region. Reduced summer snow-retention has favoured seedling establishment and juvenile growth, and mild winters with reduced risk of frost-desiccation have enhanced survivorship and height increment.

Camarero and Gutiérrez (2004) studied the effect of climate, mainly air temperature, on tree recruitment and recent treeline dynamics in the Spanish Pyrenees, dominated by *Pinus uncinata* at local spatial and short temporal scales. The result show that treelines were ascending until a period of high interannual variability in mean temperature started (1950–95). During the late twentieth century, treeline fluctuation was less sensitive to climate than was the change in tree density within the ecotone. Tree recruitment and treeline position responded to contrasting climatic signals; tree recruitment was favored by high March temperatures whereas treeline position ascended in response to warm springs.

Bekker (2005) examined the role of feedback between existing trees and the establishment and survival of seedlings in the advancement of linear, finger-like strips of subalpine forest in Glacier National Park, Montana, USA. Overall advancement rates ranged from 0.28 to 0.62 m/yr. Feedback was critical for the survival of seedlings before 1800, and strongly controlled advancement between about 1800 and 1850, but appears to have had little effect on establishment patterns since that time.

Dalen and Hofgaard (2005) found a differential regional treeline dynamics in the Scandes Mountains. Main tree establishment occurred during the 1940s in the southern and northernmost regions, and during the 1960s in the middle region. Age distribution patterns showed stable or possibly progressive treelines in the southern and middle regions but recent recession in the north.

Gehrig-Fasel et al. (2007) found a significant increase of forest cover in the treeline ecotone of Swiss Alps. With 90% ingrowth, they identified both land use and climate change as likely drivers. Most of the upward shift occurred within a band of 300 m below the potential regional treeline, indicating land use as the most likely driver. Only 4% of the upward shifts were identified to rise above the potential regional tree line, thus indicating climate change.

Camarero and Gutierrez (2007) studied the recruitment processes in an isolated population of *Pinus uncinata* Ram. located at the southwestern limit of the species' distribution in Europe (Iberian System, NE Spain). The main episodes of tree establishment were coincided with low radial growth during a period with reduced grazing pressure. They suggested that late summer temperatures might have a non-linear negative threshold effect on recruitment rather than a linear effect.

Danby and Hik (2007) found an increased tree density as well as an advancement of Spruce (*Picea glauca*) treeline elevation by 65–85 m on south-facing slopes in south-west Yukon, Canada during the early to mid-20th century but treeline did not advance on north-facing slopes though stand density increased 40–65%.

Kullman (2007) reported a demographic trends of *Pinus sylvestris* L. (Scots pine) treeline populations by monitoring for a period of 32-year (1973–2005) in the Swedish Scandes. The size of the entire sampled population increased by 50% during the 32-year observation period and thereby pine become a more prominent element on the landscape.

Batllori and Gutiérrez (2008) studied twelve *Pinus uncinata* treeline populations on the Iberian eastern range of the Pyrenees. They observed past and recent synchronous recruitment (mid-19th century, second half of the 20th century) trends of *Pinus uncinata* with climate change at the treelines in the Iberian eastern range of the Pyrenees. The ecotone densification since the 1950s occurred in the context of climatic warming and substantial land use abandonment. In 50% of the surveyed treelines, ecotone densification has been coupled to tree limit shifts in the recent past.

Batllori et al. (2009) studied *Pinus uncinata* treeline ecotones in the Catalan Pyrenees (north-east Spain) and Andorra. They tested whether krummholz individuals influence regeneration at the treeline by performing a transplantation field experiment to evaluate the extent of facilitation on seedling survival and growth in height. Their results suggest that scarce availability of safe sites and uneven facilitation by krummholz control seedling recruitment patterns within alpine treeline ecotones. Such constraints may distort or counter the response of treeline ecotones to climate warming at local and regional scales.

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.

Bogärt et al. (2010) recorded decadal colonization and recent expansion of aspen (*Populus tremula* L.) in subarctic Sweden. Over the past 100 years, aspen became about 16 times more abundant, mainly as a result of increased sexual regeneration. Disturbance to the birch forest by cyclic moth population outbreaks was critical in aspen establishment in the subalpine area.

Bogärt et al. (2011) found 50% of studied treeline sites in Torneträsk area in northern Sweden being advanced in last century with an average treeline shift of 24 m upslope (+0.2 m/yr), maximum treeline advance of +145 m (+1.5 m/yr in elevation and +2.7 m/yr in actual distance, whereas maximum retreat was 120 m downslope.

Kirdyanov et al. (2012) observed an upslope shift of the *Larix gmelinii* treeline position by approximately 30–50 m in altitude in the Putorana Mountains, northern Siberia during the last century.

Öberg and Kullman (2012) analyzed short term (2005/2007−2010/2011) performance of mountain birch (*Betula pubescens* ssp. *czerepanovii*) treeline along a regional climatic maritimity-continentality gradient in the Swedish Scandes. Treeline upshifted by 3.0 m/yr in the maritime part while it was retreated by 0.4 m/yr in the continental part of transects. The birch treeline expands upslope as the alpine snow patches shrink, but continue to provide sufficient melt water throughout the summer.

Mamet and Kershaw (2012) studied subarctic and alpine treeline dynamics during the last 400 years in Taiga Cordillera of the western Mackenzie Mountains in the Northwest Territories, and the western Hudson Bay Lowlands in northern Manitoba, Canada. Treeline locations advanced and stand density increased during the early-to-mid-20th century around Churchill, although responses were not uniform across sites or species. Correlation analyses with temperature suggest that conditions during establishment and particularly during recruitment are crucial for controlling treeline dynamics. The study also indicated that site- and species-specific responses play a large role in determining the treeline response at multiple scales, illustrating the complexity of treeline dynamics in the context of a changing climate.

Hofgaard et al. (2013) found an average northward advance of the birch and pine forest lines of 156 and 71 m/yr, respectively in response to climate warming in northernmost Norway since the early 20th century. The birch treeline showed the most pronounced advance (340 m/yr), whereas the pine tree line showed very limited advance (10 m/yr).

Aakala et al. (2014) observed a prominent stepwise advance of the *Pinus sylvestris* treeline in northeast Finland with slow increase in treeline in the beginning of 20th century (0.5 m/yr) and more rapid advance later (1.4 m/yr).

2.2.3 Treeline research in the Himalayas and adjacent Mountain areas

Several studies have been carried out on the treeline ecotone of the Chinese mountains (Wang et al., 2006; Baker & Moseley, 2007; Liang et al., 2011; Gou et al., 2012; Lv & Zhang, 2012; Wang et al., 2013; Zhao et al., 2013; Shen et al., 2014). Baker and Moseley (2007) documented changes in alpine treeline and glacial recession in northwestern Yunnan, China by using historic climate data and repeat photographs. Repeat photos and supplemental measurements show that warming in the region is causing the retreat of glaciers and contributing to the elevational advance of alpine treeline. Field based studies have reported very little shifting of treelines from Tibet and adjacent mountainous regions of China with climate change (Wang et al., 2006; Liang et al., 2011; Gou et al., 2012; Lv & Zhang, 2012). Lv and Zhang (2012) found a significant tree recruitment of *Abies spectabilis* 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 treeline on the Sygera Mountains, southeastern Tibetan plateau. But they did not find significant upward movement in fir treelines in the Tibetan plateau despite the warming in the region in the past 200 years. From a study in two *Juniperus przewalskii* treeline sites in the eastern part of the Qilian Mountains, northeastern Tibetan Plateau, Gou et al. (2012) found that a high temperature favors tree growth, increase in tree density at treeline, and an advance in treeline position. They found positive correlations between ring-width and mean monthly air temperatures in current and previous June, July and August. The number of trees established coincides with temperature changes. In Qilian Mountains, the warming trend after the Little Ice Age favored increase in tree density and an advance of treeline.

Wang et al. (2006) found that both temperature and precipitation influence positively for both the radial growth of trees and tree recruitment *Picea schrenkiana* in the central Tianshan Mountains, northwestern China, but the patterns of their responses differed. Consecutive years of high minimum summer temperatures and high precipitation during spring mainly influenced for the *Picea schrenkiana* recruitment. Over the last several decades, the treeline did not show an obvious upward shift with lack of new recruitment. Recruitment increased until the early 20th century (1910s) but then decreased with poor recruitment over the past several decades (1950–2000).

2.2.4 Treeline research in Hindu Kush Karakorum Himalaya

Compared to the other mountain regions, treeline research in the Hindu Kush Karakorum Himalayas (HKKH) region is still at infant stage and fragmentary. Data gap exists in the many aspects of treeline formation and dynamics in the HKKH region (Schickhoff, 2005). Few studies based using remote sensing and GIS tools, dendroecological tools, found tree regeneration in the region. These available studies have reported increase in tree density as well as altitudinal range shift.

Dubey et al. (2003) studied the upward shifting of *Pinus wallichiana* in the western Himalayas, India. They found that the *P. wallichiana* has shifted by 19 and 14 m per decade on south and north facing slope, respectively.

Panigrahy et al. (2010) studied the vegetation ingression and land cover changes in Nanda Devi Biosphere Reserve in Central Himalaya using satellite imagery of 1986, 1999 and 2004. The 1999 imagery showed marginal increase in vegetation cover while 2004 imagery revealed >20% increase in the vegetation cover and drastic reduction in snow cover, thereby showing vegetation ingression in former snow/ice areas. The elevation contours, overlaid on the 2004 imagery, showed the timberline at 4300 m, the alpine scrub line at 4900 m and the tundra vegetation line at 5300 m. The topographic map of 1960 showed scrub, scattered trees and timberline between 3900 and 4000 m. The study indicates rapid recession of glaciers and snow cover and ingression by vegetation probably due to global warming related rise in temperature.

Singh et al. (2011), based on an analysis of the satellite imagery, found an evidence of upward shift in the alpine tree and vegetation ecotone as well stand densification at treeline in Gangotri catchment over three decades. They found that the treeline extracted from satellite imagery has moved up about 327 ± 80 m and other vegetation boundries have moved up about 401 ± 77 m in three decades. The vertical rate of treeline shift was 11 m/yr with reference to 1976 treeline; however, this can be 5 m/yr if past toposheet records (1924–45) are considered as reliable reference. Bioclimatic niche modelling of the *Betula utilis* based on future IPCC scenario suggests that treeline could be moving upward with an average rate of 3 m/yr. In addition to an upward shift of vegetation in the alpine zone of Himalayas. The study also indicated a densification within the existing vegetation ecotones.

Singh et al. (2012) monitored the alpine treeline shift in Uttarakhanda parts of the Indian Himalayas using remote sensing and found rapid treeline shift in recent years. The mean upward shift of the treeline was 388 ± 80 m since 1970s. The mean upward shift of the treeline was highest in Chamoli District (430 m) and lowest (360 m) in Uttarkashi and Bageshwar districts.

Bharti et al. (2012) studied the changes in the timberline ecotone vegetation of Nanda Devi National Park, India since 1980 to 2010. This study based on remote sensing analysis of Landsat MSS and TM images suggests no geographical shift in the upper limit of timberline, while the subalpine forest’s canopy has increased substantially.

Rai et al. (2013) carried out an ecological assessment of timberline vegetation during 2008–2011 at selected locations of Uttarakhand and Himachal Pradesh in the Indian Himalaya. Geospatial analysis of the timberline ecotone (3,000–4,000 m asl) showed that fir (*Abies spectabilis*) occupied the greatest area within the timberline followed by oak (*Quercus semecarpifolia*), birch (*Betula utilis*), and krummholz. Study also revealed that an area of approximately 81 km^2 had undergone major change during the last three decades, with a proportionally greater change in the last ten years than in the previous decades. Fir forest is increasing since 1980. The phenological study showed that the broadleaf deciduous species *Betula utilis* was more sensitive to interannual climatic variation and early snow melt.

Singh et al. (2013) modeled the environmental niche of a dominant treeline species (*Betula utilis*) in alpine region of Indian Himalaya using satellite remote sensing technique. The result demonstrates the ability of the niche models in assessing the probable extent of Himalayan birch distribution and its presence in treeline ecotone of Uttarakhand in Indian Himalaya.

Ghimire and Lekhak (2007) studied the regeneration of the *Abies spectabilis* in the northern aspect of the Manang valley (elevation 3500-4000 m asl). The size class distribution of *A. spectabilis* resembled the reverse J-shaped curve. However, there was lack of large girth class trees. Seedling and sapling density was abundant but regeneration potential was low under its own canopy.

Shrestha et al. (2007) studied distribution and community structure of *Betula utilis* forest in treeline region in a trans-Himalayan dry valley in Manang (central Nepal). They reported that moisture plays an important role in spatial (horizontal) distribution of *B. utilis*. They infer that if not severely disturbed, mixed *B. utilis* forest may be replaced by *Abies spectabilis*. *B. utilis* was regenerating; however, the distribution of seedlings and saplings was spatially heterogeneous, and appeared to depend on canopy cover. The *B. utilis* seedlings could not establish under their own closed canopy even if they produced viable seeds. Partial canopy opening may induce seedling establishment and hence continuous regeneration of *B. utilis* at mature stands.

Bhuju et al. (2010) studied the stand structure and population demography of *Abies spectabilis* and *Betula utilis* in treeline and timberline regions of Sagarmatha National Park. They found higher regeneration in timberline sites than at treeline.

Gaire et al. (2011) studied the treeline dynamics of *Abies spectabilis* in Langtang National Park. From the size class distribution and population demography analysis, they found a high recent regeneration of *A. spectabilis* in the treeline ecotone. They also indicated towards the potential upward shifting of the treeline ecotone in future along with climate change.

Chhetri and Cairns (2015) studied treeline ecotone dynamics of *Abies spectabilis* in north, south and east aspects in the Barun valley, Makalu Barun National Park, eastern Nepal Himalaya. They found that most trees being established in the early 20th century and establishment in the second half of the 20th century was confined to the forestline area. Treeline position was advanced very slowly with only 22 m average elevational shift in the last 130 years, and with average current shifting rate of 14 cm/yr.

Schickhoff et al. (2015) reviewed the current state of knowledge regarding sensitivity and response of Himalayan treelines to climate warming. Near-natural treelines are usually krummholz treelines, which are relatively unresponsive to climate change. They found an intense recruitment in treeline, indicating a great potential for future treeline advance. Competitive abilities of seedlings within krummholz thickets and dwarf scrub heaths will be a major source of variation in treeline dynamics. Tree growth–climate relationships show mature treeline trees to be responsive to temperature change, in particular in winter and pre-monsoon seasons. Ecological niche modelling indicated that bioclimatic conditions for a range expansion of treeline trees will be created during coming decades.

Shrestha et al. (2015) investigated the treeline dynamics at two environmentally contrasting areas of Manang and Langtang in the Nepal Himalaya. Despite differences in moisture regimes, tree species and recent climate trends in two areas, they found very similar treeline dynamics over the past six decades. In both areas, treelines were stationary over the past six decades. They hypothesized that the stationary *Abies spectabilis* treeline in mesic area of Langtang is regulated by non-climatic factors, notably grazing. The stationary to weakly receding *Pinus wallichiana* treeline is the result of increasing climatic variability and some very cool summers in the recent decades.

2.3 Dendrochronology

2.3.1 Introduction

Dendrochronology (word derived from Greek: Dendron-tree limb; khronos-time and, logia-study) is defined broadly to include all tree ring studies where the annual growth layers have been assigned to or are assumed to be associated with specific calendar years (Fritts, 1976; Speer, 2010). Dendrochronology or tree-ring dating is the scientific method of dating based on the analysis of patterns of tree-rings. Dendrochronology can date the time at which tree rings were formed to the exact calendar year. It is the interdisciplinary science with wider applications.

Tree rings are an exceptionally valuable source of paleo-climatic information and tree ring data can be used to reconstruct the yearly variations in climate that occurred prior to the interval covered by direct climatic measurements (Fritts, 1976). The climate phenomena seen through tree rings have spatial scales from a few hectares to a hemisphere, and temporal scales from the few hours of an ice-storm, through decades of drought, to centuries of changed global atmospheric circulation (D'Arrigo et al., 2001; Hughes, 2002; Cook et al., 2010, 2013; Speer, 2010; PAGES 2k Consortium, 2013).

Growth rings also referred to as tree rings or annual rings, can be seen in a horizontal cross section cut through the trunk of a tree (Fritts, 1976; Speer, 2010). Growth rings are the result of new growth in the vascular cambium, a layer of cells near the bark that is classified as a lateral meristem. Visible rings result from the change in growth speed through the seasons of the year, thus one ring usually marks the passage of one year in the life of the tree (Fritts, 1976; Speer, 2010). The rings are more visible in temperate, subalpine and alpine zones, where the seasons differ more markedly.

As with any science, dendrochronology is governed by a set of principles or scientific rules (Fritts, 1976; Speer, 2010). Some are specific to dendrochronology while others are basic to many disciplines. Dendrochronology is based on some of these basic principles and concepts: The Uniformitarian Principle, Principle of Aggregate Tree Growth, Principle of Limiting Factor, Concept of Ecological Amplitude, Site Selection, Sensitivity, Cross Dating, Repetition, Standardization, Modeling Growth-Environmental Relationships, and Calibration & Verification, etc. (Fritts, 1976; Speer, 2010).

2.3.2 Brief history of dendrochronology

Dendrochronology is a young discipline in the domain of science (Fritts, 1976; Speer, 2010). In spite of its recent modern history the idea that tree produce annual rings had been suggested since time of Theophrastus (372-287 BC) (Speer, 2010). Theophrastus who was a pupil of Aristotle wrote "History of Plants" in nine volumes and last volume entitled "Causes of Plants" mentioned growth rings in two fir species (Speer, 2010). In late 1400s, Leonardo da Vinci described annual ring formation and suggested tree ring is related to weather (Speer, 2010). Andrew E. Douglass (1867-

1962 AD), the founder of the Laboratory of Tree-Ring Research (Est. 1937 AD) at the University of Arizona, is regarded as the father of Dendrochronology (Fritts, 1976; Speer, 2010). By the early 1920s, Douglass had pioneered the science of dendrochronology, most importantly, the principle of crossdating which he applied to a variety of different disciplines from climatology to astronomy to archaeology. Other pioneer scientists that explored tree rings include Duhamel and Buffon, Alexander Catlin Twining, Theodor Hartig, Robert Hartig, Charles Babbage, Jacob Kuechler, V.C. LaMarche Jr., Hal C. Fritts, Fritz H. Schweingruber, etc (Speer, 2010). In the Himalayan region, the history of the subject especially for climate reconstruction is very young as compared to other region because it was started in 1980s (Ahmed, 1989; Bhattacharyya & Shah, 2009). In case of Nepal, collection of tree cores was started at the end of 1970s (Bhattacharyya et al., 1992) with some efforts in late 1990s and early 2000s (Regmi, 1998; Khanal & Rijal, 2002); however, systematic and institutional study was started much later i.e. in 2009 AD (Gaire et al., 2013).

2.3.3 Parameters used in dendrochronology research

A variety of structural characteristics of tree rings, such as width (earlywood, latewood and annual or total) (Cook et al., 2003; Gaire et al., 2014; Shah et al.; 2013, 2014), wood density (Earlywood, latewood & average) (Schweingruber et al., 1978; Schweingruber, 1990; Brauning, 2004; Sano et al., 2005; Fan et al., 2008), wood anatomical features like vessel size, mean vessel area, tracheid-lumen, ray parenchyma (Eckstein & Frisse, 1982; Fonti et al., 2010; Oladi & Pourthmasi, 2012; Oladi et al., 2014), and stable isotopes of oxygen, hydrogen and carbon (Lepp, 1975; Long, 1982; Ramesh et al., 1986; Leavitt, 2010; Sano et al., 2010; Shi et al., 2011) are widely used parameters because they show ring to ring variability. The variations in ring width have been studied most often (Fritts, 1976; Suzuki, 1990; Bhattarcharyya et al., 1992; Cook et al., 2003; Shah et al., 2007, 2014; Bhuju et al., 2010; Gaire et al., 2011, 2014), because width can be observed and measured easily from a finely sanded or microtomed surface by using a hand lens or dissecting microscope.

Early in the 1960s, Polge (1970) discovered that a thin section of wood can be X-rayed, and the image on exposed film scanned by an optical densitometer to obtain detailed ring density measurements (Fritts & Swetnam, 1989). Parameters such as minimum density, maximum density, early wood width and latewood width are now derived from these types of measurements. These can be correlated with climatic variations as well as various physical, chemical and biological features of the environment (Fritts, 1976; Sano et al., 2005). Detail procedure on sample preparation and analysis using radiodensitometry can be found in many literatures including Schweingruber (1990).

In areas of little width variation, dendrochronology is becoming possible only because of the greater variability in density measurements (Fritts & Swetnam, 1989). Densitometric analysis appears to offer considerable promise for environmental and climatic analysis of moderately moist forest habitats such as the central deciduous forest and southern boreal forest of North America, forests of Western Europe (Fritts & Swetnam, 1989) as well as from the Himalayas (Bhattarcharyya et al., 1992; Pant et al., 2000; Bräuning, 2004; Sano et al., 2005). In moist region, the rings may be wide and the widths may exhibit much less variability than wood density characteristics. The implementation of densitometry for studies in more extreme sites may not be practical, because the rings from many old trees growing on stressed sites are sometimes too small to be resolved by the densitometer. However, recent advancement in image analysis techniques have overcome this problem (Fritts & Swetnam, 1989). If we collect sample and mount cores in a manner that allows for both ring-width and densitometric work (Sano et al., 2005).

In recent years, different microtomes, and image analysis programs and softwares have been developed that can be used in wood anatomy and dendrochronology (Gärtner & Nievergelt, 2010; Liang, et al., 2013; Gärtner et al., 2014; van Arx & Carrer, 2014). For example, they not only are used to measure ring width distances but also to calculate number and size of vessels / tracheids in a tree ring (van Arx & Carrer, 2014). Among the various softwares, Image-J is a public domain, Java-based image processing program developed at the National Institutes of Health, Maryland, USA and is downloadable from internet, free of charge.

Environmental processes captured in tree rings can be stored chemically. Chemical properties involve (1) individual elements, (2) chemical compounds, and (3) stable isotopes (McCarroll & Loader, 2004). Stable isotopes in tree rings could provide palaeoclimate reconstructions with perfect annual resolution and statistically defined confidence limits (McCarroll & Loader, 2004). The three main elements in wood (Carbon, Oxygen and Hydrogen) all have more than one stable (non-radioactive) isotope. Carbon has two stable isotopes, ^{12}C and ^{13}C, each with six protons but with either six or seven neutrons. Hydrogen has two stable isotopes, the heavier one being called deuterium (2H or D). Similarly, Oxygen has three isotopes i.e. Oxygen 16, Oxygen 17, and Oxygen 18. These have 8 protons and 8, 9 (rare) and 10 neutrons respectively. It is the ratio of ^{18}O to ^{16}O that has traditionally been used in the environmental sciences (McCarroll & Loader, 2004). Stable Carbon isotopes record the balance between stomatal conductance and photosynthetic rate, dominated at dry sites by relative humidity and soil water status, and at moist sites by summer irradiance and temperature. Stable Oxygen and Hydrogen isotopic ratios record source water which contains a temperature signal and leaf transpiration controlled dominantly by vapour pressure deficit (McCarroll & Loader, 2004). Stable and unstable isotopes of Oxygen, Hydrogen and Carbon in tree rings are widely used as other promising sources of past climatic information (egs. Lepp, 1975; Ramesh et al., 1986; McCarroll & Loader, 2004; Sternberg, 2009; Leavitt, 2010; Sano et al., 2010, 2012; Shi et al., 2011, 2012).

2.3.4 Applications of dendrochronology

Dendrochronology is a versatile and interdisciplinary science so as environmental science with wider applications in the various aspects of environmental change studies including past climate reconstruction. It has several branches or subfield specialized in particular discipline with the prefix ‘dendro’ added to them namely Dendroarchaeology, Dendroclimatology, Dendroecology, Dendrogeomorphology, Dendroglaciology, Dendrohydrology, Dendroentomology, Dendrovolcanology, Dendrochemistry, Dendromastecology, Dendrosesmology, Dendropyrochronology, Gender in dendrochronology, Wood anatomy in dendrochronology, and so on (Speer, 2010). Some sub-disciplines related to this study are briefly mentioned here.

Dendroclimatology: The science that uses tree rings to study climatic response of trees, study present climate and reconstruct past climate (Speer, 2010). Example: analyzing ring widths of trees to determine how much rainfall fell per year long before weather records were kept or how temperature changed during past, reconstruction of past droughts and so on (egs. Cook et al., 2003, 2010, 2013; Sano et al., 2005, 2010; 2012; Shah et al., 2007; Singh et al., 2009; Managave et al., 2010; Shi et al., 2012; Yadav, 2011, 2013; Thapa et al., 2014).

Dendroecology: The science that uses tree rings to study factors that affect the earth's ecosystems (Speer, 2010). Example: study of processes such as treeline movement, forest patch dynamics, regeneration, population demography, productivity assessment, insect outbreaks, or movement of invasive tree species, effects of air pollution on tree growth by studying changes in ring widths over time, etc. (egs. Berg et al., 2006; Bhuju et al., 2010; Speer, 2010; Gaire et al., 2011, 2014; Stravinskiene et al., 2013).

2.3.5 Dendrochronological study in the Hindu Kush Karakoram Himalayan (HKKH) region

In HKKH region, the history of the subject especially for climate reconstruction is very young as compared to other regions. Dendrochronological study in the region was first initiated in India. Studies on tree rings in India in forestry aspects such as the evaluation of growth rates, wood productivity and quality, or rotation cycles have been recorded since long back (Gamble, 1902 cited Bhattacharyya & Shah, 2009), but systematic tree-ring research based on accurate dating of long sequences of growth rings had only been started since the end of the 1980s (Bhattacharyya & Shah, 2009). In Pakistan the field of dendrochronology was started its steps during 1980s (Ahmed, 1989). In case of Nepal collection of tree cores started at the end of 1970s, however, institutional study is started much later i.e. 2009 in NAST (Gaire et al., 2013).

Compared to the other HKKH countries, dendrochronological study in India has long history. Bhattacharyya and Shah (2009) reviewed the literature and provided the past studies, current state and future prospects of dendrochronological study in India. Studies on tree rings in India have been recorded since long back but systematic tree-ring research based on accurate dating of long sequences of growth rings had only been started since the end of the 1980s (Bhattacharyya & Shah, 2009). The dendrochronological studies from the India have used several coniferous and some broadleaved species like *Abies pindrow*, *A. spectabilis*, *Betula utilis*, *Cedrus deodara*, *Juniperus* sps., *Pinus* sps., *Picea smithiana*, *Taxus baccata*, *Tectona grandis*, etc. (Bhattacharyya & Shah, 2009; Shah et al., 2014). These studies have used various macro and micro structural parameters like ring-width (total earlywood and latewood width), wood density (earlywood, latewood and total ring wood), stable isotopes (Carbon, Oxygen and Hydrogen), and vessel area and cell size (Ramesh et al., 1985, 1989; Pant et al., 2000; Bhattacharyya et al., 2007). Dendrochronological studies have covered several subdisciplines like dendroecology, dendroclimatology, dendrohydrology, dendrogeomorphology, dendroseismology, dendroarchaeology, etc. There is considerable progress in the dendroclimatological study in India. Studies have also tested the seismological potential of the many taxa from the region (Yadav & Bhattacharyya, 1994; Bhattacharyya et al., 2008). Some of these taxa have already proved suitable for climate reconstruction, particularly the reconstruction of seasonal variation of temperature and precipitation. These studies also reveal that tree-ring data of conifers in the Himalayan region are a suitable proxy mostly for the reconstruction of pre-monsoon temperature and precipitation. Several studies from western and eastern Himalayas have reconstructed different monthly or seasonal temperature (Yadav et al., 1997, 1999, 2004; Yadav & Singh, 2002; Krusic et al., 2015; Zafar et al., 2015), precipitation (Singh & Yadav, 2005; Singh et al., 2006, 2009; Sano et al., 2013; Yadav et al., 2014) and river flow (Cook et al., 2013; Shah et al., 2013; Singh & Yadav, 2013). Tree ring widths have been widely used to reconstruct past precipitation and temperatures in western (Indian) Himalayan regions (e.g., Singh & Yadav, 2005; Yadav et al., 1999, 2004; Yadav, 2011a & b). However, dendroclimatic reconstructions for the central and eastern Himalaya are rather scant, owing largely to the paucity of long meteorological records and the reduced climate sensitivity of tree ring data associated with relatively abundant rainfall (Bhattacharyya & Shah, 2009). These studies have reconstructed temperature and precipitation of different seasons like spring (April-May) (Singh & Yadav, 2005); late summer (August-September) (Bhattacharyya & Chaudhary, 2003; Shah et al., 2007) and the growing season (April-September). There is no specific trend in this reconstructed climate of the region. However, there are very limited studies on the treeline dynamics from the Indian Himalayas using dendrochronology technique (Dubey et al., 2003).

Compared to India, history of dendrochronological study in Pakistan has relatively young as studies on tree rings were started in 1985 AD (Ahmed, 2014). After that several studies have been carried out to test the dendrochronological potential of the trees growing in the Karakoram and Himalayas. The dendrochronological studies from Pakistan have mainly used coniferous species *Abies pindrow, Cedrus deodara*

(D. Don) G. Don, *Juniperus excelsa* M. Bieb., *Pinus gerardiana* Wall. ex D. Don., *Pinus roxburghii* Sargent, *Pinus wallichiana* A.B. Jackson and *Picea smithiana* (Wall.) Boiss (Ahmed et al., 2011). The *Picea smithiana* is most widely studied species in the region. Early studies were focused to test the dendroclimatological potential of the species (Ahmed, 1988, 1989; Khan et al., 2008; Zafar et al., 2010; Bokhari et al., 2013), however in the recent years good progress is seen in the hydro-climate reconstruction using tree rings (Cook et al., 2013; Zafar et al., 2015). Dendrochronological studies in Pakistan have covered several subdisciplines like dendroecology, dendroclimatology, dendrohydrology, dendrogeomorphology, dendroseismology, dendroarchaeology, etc. Bokhari et al. (2013) tested dendroseismological potential of five pine tree species of Azad Kashmir, Pakistan, i.e., *Abies pindrow* Royle, *Cedrus deodara*, *Pinus wallichiana*, *Pinus roxburghii* Sargent, *Picea smithiana*. Group of missing/double rings and abrupt growth change was recorded in various wood samples with a clear wound scars showing some sort of past disturbance. Ahmed et al. (2012) analyzed the climate-growth relationships of four gymnosperm tree species growing in seven catchments in the Indus Basin of the Karakorum Range, North Pakistan and found a strongest climate signal in *Pinus gerardiana*. Winter and spring precipitation showed a pronounced positive correlation with tree growth while an inverse response to spring temperature. Of the two climate parameters (temperature and rainfall) the strongest response was seen to rainfall. Cook et al. (2013) reconstructed river discharge levels of Indus River covering the period 1452–2008 AD using a network of tree-ring sites from the Upper Indus Basin. This 557-year record displays strong inter-decadal fluctuations that could not have been deduced from the short gauged record. Recent discharge levels are high but not statistically unprecedented and are likely to be associated with increased melt water from unusually heavy prior winter snowfall. A period of prolonged below-average discharge was indicated during 1572–1683 AD. Zafar et al. (2015) reconstructed nearly five centuries (1523–2007 CE) long summer (June–August) temperature using a tree-ring chronologies from the Karakorum in northern Pakistan. They used ring width chronologies of *Picea smithiana* and *Pinus gerardiana* from middle-to-upper timberline sites in the northern Karakorum valleys of Gilgit and Hunza (2850 to 3300 m asl). The study indicated that Karakorum temperature has remained decidedly out of phase with hemispheric temperature trends for at the least the past five centuries, the long-term stability is regarded as Karakorum Anomaly. The region's temperature and cloudiness are contributing factors to the anomaly.

Bhutan is an undisturbed, pristine Himalayan country with more than 70% of the country occupied by forest. Hence, there is a great prospect of various dendrochronological researches. However, dendrochronological study in Bhutan is still in an infant stage because such study compared to other HKKH region is started much later. Very few dendrochronological studies from Bhutan can be found (Cook et al., 2010; Sano et al., 2013; Krusic et al., 2015). Cook et al. (2010) developed the ring width site chronologies from the Bhutan and used for Monsoon Asia Drought Atlas preparation. Sano et al. (2013) developed a 50-year tree ring δ^{18}O chronology for each *Juniperus indica*, *Larix griffithii*, and *Picea spinulosa* using a total of 12 trees (four trees per species) from the Bhutan Himalaya. Response analyses reveal that tree ring δ^{18}O values are controlled mainly by summer precipitation, irrespective of species. Based on these results, they established a robust 269-year δ^{18}O chronology to reconstruct the amount of May–September precipitation based on data from four larch trees. Correlation analyses reveal that the El Niño–Southern Oscillation (ENSO) plays an important role in modulating summer precipitation in Bhutan. Recently, Krusic et al. (2015) developed a small network of tree ring chronologies from Bhutan and presented the first multi-centennial (638 year from 1376–2013 AD) tree ring based summer (June–August: JJA) temperature reconstruction for Bhutan. Relative to the 1950–2013 AD average summer temperature, three prominent cold periods were recorded, two in the mid-15th century, and one in the late 17th century. The warmest period began in the first decade of the 21st century coinciding with the timing of general glacier recession in the eastern Himalaya that continues to the present (Krusic et al., 2015). The Bhutan temperature reconstruction exhibits a significant correlation to known volcanic eruptions and anomalously cold periods appear to align with solar irradiance minima in the 15th, late-17th, and early-19th centuries, implying a link between solar variability and decadal-scale temperature variability (Krusic et al., 2015).

2.3.6 Dendrochronological studies in Nepal

The wide array of habitats representing major biomes of the world in a small geographical area in graded climates in mountainous topography of Nepal and cultural diversity of the country provides a great potential in multidimensional tree ring research. This section tries to disclose the various aspects of so far conducted tree ring studies from Nepal including type of methodology used, temporal and spatial coverage of studies, studied species, chronology length and scope of study. In Nepal, more than 60 un/published studies based on tree-ring analysis have been found (Gaire et al., 2013). Various aspects of tree ring studies covered in Nepal are analyzed in following sub headings.

2.3.6.1 Methodological aspect

So far conducted studies have covered wider methodological aspects. Most of the studies, almost all from Nepali researchers, have used ring width as a parameter for past dendrochronological studies in Nepal. Some studies (Bräuning, 2004; Sano et al., 2005) have used wood densitometry (X-ray densitometry) technique to calculate the density of early wood, late wood and total wood of each tree ring. Only two studies (Sano et al., 2010, 2012) have used stable isotope in tree ring for studying past climate change. No study was found using wood anatomical features for past environmental studies. These studies suggested that combination of wood densitometry and isotope analysis, besides ring width parameter, is best and appropriate approach for tree ring studies in Nepal (Bhattacharyya et al., 1992; Sano et al., 2005) because using these parameters increases the number and quality of predictor variables in tree ring research.

2.3.6.2 Temporal aspect of study

Scholars from overseas started initiation of dendrochronological studies in Nepal. According to the Bhattacharyya et al. (1992), earlier tree-ring collections in Nepal initiated in the late-1970s (1979-1980) by Rudolf Zuber who collected tree ring samples of diverse species and habitats. However, in 1990 for the first time, E. Suzuki from Japan published research from Nepal. Bhattacharyya et al. (1992) elaborated the dendro study in Nepal by doing large scale sampling and described 10 ring width based chronologies and reviewed the prospects for further dendroclimatic work in Nepal. They pointed the good potentiality of some conifer tree species like: *Abies spectabilis*, *Pinus wallichiana*, *Cupressus dumosa*, *Cedrus deodara*, and *P. roxburghii* for dendroclimatic study.

Later this work is further extended by the scientists from from Columbia University, USA led by Professor Edward Cook. Cook et al. (2003) used Zuber's collected core samples as well Burghardt Schmidt's collected samples from living trees and archaeological wood in the dry inner valleys of north-central Nepal to develop master chronologies of various species. They carried out extensive and intensive sampling in Nepal and developed 32 annual tree ring chronologies using diverse tree species (Cook et al., 2003). During initial period, researchers from Central Department of Geography, Tribhuvan University also played an important role in the development of dendrochronology field in Nepal (Regmi, 1998; Khanal & Rijal, 2002). Number of dendrochronological research in Nepal increased slightly at beginning and at the faster rate in recent years (Regmi, 1998; Khanal & Rijal, 2002; Gaire et al., 2013). In 2002 the publications on tree ring studies from Nepal was seen increased and reached to six in which contribution of studies by Japanese researchers is crucial in addition to few Nepali researchers (Khanal & Rijal, 2002; Gaire et al., 2013). Studies after 2010 was found increased rapidly due to the contribution of Nepali researchers after the establishment of the first institutional Dendrochronology Laboratory in Nepal at the premises of Nepal Academy of Science and Technology in 2009 (Gaire et al., 2013).

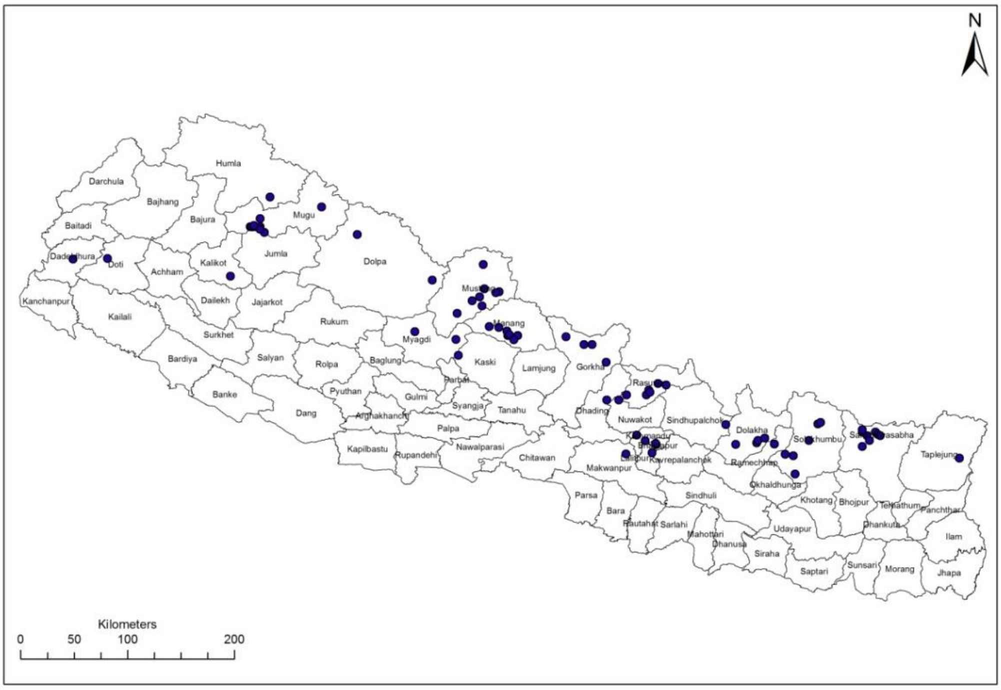


Figure 1: Map showing distribution of sites covered in sampling of dendrochronological studies in Nepal (Gaire et al., 2013)

Dendrochronological studies from Nepal have covered far-east to far-west of Nepal Himalaya (Fig.1, Gaire et al., 2013). So far, these studies covered more than 25 districts of Middle Mountain to higher Himalaya of Nepal. Elevations of the studied sites ranged from about 1000 to 4300 m asl (Gaire et al., 2013). Most of these studies are carried out from lower temperate and sub alpine forests growing below treeline (Suzuki, 1990; Bhattacharyya et al., 1992; Cook et al., 2003; Bräuning, 2004; Sano et al., 2005; Chhetri & Thapa, 2010) while some studies are from treeline (Bhuju et al., 2010; Gaire et al., 2011; Chhetri & Cairns, 2015; Shrestha et al., 2015) and subtropical region (Regmi, 1998). An initiative step is taken in Terai and Siwalik/Churiya comprising tropical and subtropical region of the country, however concrete result is yet to come. Consistent with global trend, tropical area is least explored area. Many studies are concentrated on some pocket area or region in which Langtang region come in first from where more than 10 studies have been carried out (Gaire et al., 2013). Therefore, there is a great difference in the spatial coverage of the tree ring studies in Nepal.

2.3.6.3 Species coverage and chronology length

Looking at the tree species coverage in so far conducted Dendro studies in Nepal, samples from more than 20 species like *Abies spectabilis, Acer sp, Alnus nepalensis, Betula utilis, Cedrus deodara, Juniperus indica, Juniperus recurva, Larix potanini, Picea smithiana, Pinus roxburghii, Pinus wallichiana, Rhododendron campanulatum, Sorbus sp, Tsuga dumosa, Ulmus wallichiana*, etc. have been collected (Gaire et al., 2013; Speer et al., 2016). However, tree ring chronologies can be found only for 10 species namely *A. spectabilis, A. pindrow, B. utilis, C. Deodara, J. recurva, P. smithiana, P. roxburghii, P. wallichiana, T. dumosa*, and *U. wallichiana* (Suzuki, 1990; Bhattacharyya et al., 1992; Cook et al., 2003; Dawadi et al., 2013; Gaire et al., 2013; Thapa et al., 2013; Liang et al., 2014). Among these species, *A. spectabilis* is most studied tree species which can be found in about 75% of all publications followed by *B. utilis* (22.9%), *P. wallichiana* (16.7%) and *P. roxburghii* (12.5%) (Gaire et al., 2013). Wide use of *A. spectabilis* might be due to its clear annual ring, easy for core sampling and wider distribution. Most of these studied tree species are soft wood and conifer species, only few studies are found in broad leaved trees like *Betula, Rhododendron, Alnus*, etc. Therefore, there is great prospect of multi-aspect tree ring studies in Nepal using various new tree species growing in diverse environment. Only one study can be found in shrub species i.e. *Hipphaphae tibetana* (Sharma et al., 2013).

Length of annual ring width chronologies varies from species to species (Table 1). Though different researchers developed varied length of chronologies, here only the longest chronology length for available species is present. Longest chronology for Nepal was built from *Tsuga dumosa* which has the length of 1141 year and extends from 856 to 1996 AD. The length of these chronologies can be extended back and forth doing further research.

Table 1: Length of longest master ring width chronologies of selected species from Nepal (Updated on Gaire et al., 2013)

Species	Chronology length	Duration (AD)	References
Abies spectabilis	603	1395-1997	Cook et al. (2003)
Betula utilis	458	1552-2009	Dawadi et al. (2013)
Cedrus deodara	264	1714-1978	Bhattacharyya et al. (1992)
Juniperus recurva	582	1717-1998	Cook et al. (2003)
Picea smithiana	422	1590-2012	Thapa et al. (2014)
Pinus roxburghii	297	1683-1979	Bhattacharyya et al. (1992)
Pinus wallichiana	694	1303-1996	Cook et al. (2003)
Tsuga dumosa	1141	856-1996	Cook et al. (2003)
Ulmus wallichiana	432	1566-1997	Cook et al. (2003)

2.3.6.4 Scope of study

Dendrochronology is a versatile discipline with wider applications (Fritts, 1976; Speer, 2010). Most of the tree ring researches in Nepal are carried out with the aim of reconstructions of past climate variations using tree rings, however, only few studies have succeeded to reconstruct past climate (Cook et al., 2003; Sano et al., 2005, 2012; Thapa et al., 2014). Hence, most of the research studies are limited in the response function analysis or tree growth–climate relationship analysis (egs. Suzuki, 1990; Bhattacharyya et al., 1992; Bräuning, 2004; Chhetri & Thapa, 2010; Tenca & Carrer, 2010; Dawadi et al., 2013, Thapa et al., 2013; Gaire et al., 2014; Liang et al., 2014). The main reasons of limitation of these studies in response function analysis include many missing data (lack of continuous data) and insufficient temporal coverage (short periods). The first published climatic reconstruction using tree ring data from Nepal was by Cook et al. (2003). They reconstructed past temperature of two seasons:

February–June (1546–1991 AD) and October–February (1605–1991 AD). Each reconstruction indicates the occurrence of unusually cold temperatures in 1815–22 AD, which coincides with the eruption of Tambora in Indonesia. The multi-centennial temperature variance adjusted reconstructions reflect patterns of temperature variability associated with Little Ice Age cooling and warming into the 20th century, with the October–February season exhibiting the strongest increase in temperature over the past ~400 years. Only the October–February season shows any evidence for late-20th century warming, whereas February–June temperatures have actually cooled since 1960 (Cook et al., 2003). Later, Sano et al. (2005) reconstructed the climate of western Nepal for the past 249 years by using the relationship between climate and ring width and wood density of *Abies spectabilis*; result shows 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. Another study inferred from a $\delta^{18}O$ tree-ring chronology from *A. spectabilis* by Sano et al. (2012) has shown increasing aridity over the past 223 years in the Nepal Himalaya. Thapa et al. (2014) developed a 422-year (1591–2012 AD) long tree-ring width chronology from *Picea smithiana* (Wall.) Boiss in Khaptad National Park and reconstructed March–May average temperature for the past 373 years (1640–2012 AD). This temperature reconstruction identified several periods of warming and cooling but did not show the significant pattern of cooling during the Little Ice Age but there were few cold episodes recorded.

Dendroecology is also an important sub discipline of dendrochronology. Considerable recent progress is seen in this field (Bhuju et al., 2010; Gaire et al., 2011, 2014; Chhetri & Cairns, 2015; Shrestha et al., 2015; Schickhoff et al., 2015). These studies have focused in treeline dynamics as well as regeneration. Some studies found differential regeneration and growth rate in treeline and timberline of Khumbu region (Bhuju et al., 2010) and some found different regeneration above and below treeline (Bhuju et al., 2010; Chhetri & Cairns, 2015; Shrestha et al., 2015). Most of these studies have reported increased tree density as well as upward shifting of *Abies spectabilis* with a range of 14 cm/yr to 3.4 m/yr in different region of the Nepal (Suwal, 2010; Gaire et al., 2011, 2014; Chhetri & Cairn, 2015; Shrestha et al., 2015; Schickhoff et al., 2015). Dendroecology is very crucial sub-discipline because of data gap as well as practical implications of the knowledge derived from the tree-ring studies in various issues like climate change adaptation and forest or ecosystem management.

Dendroarchaeology involves in the study of past cultures, civilizations as well as past climate by using the tree ring samples used in the archaeological sites (Fritts, 1976; Speer, 2010). These kinds of studies were also carried out in Nepal from 1980s decade in an initiation of Burghardt Schmidt, Achim Bräuning, Thomas Wazny and Kuber Malla (Schmidt, 1992-93; Gutschow, 1994; Schmidt et al., 1999). They have carried out extensive sampling of tree cores from archaeological excavations, old houses, monasteries and castles of high altitude regions of the country including Mustang, Dolpa and Khumbu. From the study of tree ring of pine wood sample used in the monastery of Muktinath, Schmidt (1992-93) found that the woods used in the construction of the monastery (the youngest tree ring before being chopped down) was felled in 1906 AD and a specimen from the foundations of the king's palace in Dzarkot was found to be felled in 1512 AD. Schmidt et al. (1999) established a master chronology for Nepal covering the time-span between 1324 to 1997 AD that can provide important information about the history and dynamics of the local settlements, local architecture, castles and monasteries along this old and famous trade route between Tibet and India. Their result indicated the wider prospects of the dendroarchaeological studies in Nepal. Bhuju and Gaire (2012) studied the old pine stand of Kathmandu valley (Sallaghari Bhaktpur, Singhdurbar, and Thapathali) and reported the plantation history of these locations.

Different stable isotopes trapped in the tree rings can provide valuable information of the past climate or environmental change (McCarroll & Loader, 2004). Studies of this isotope analysis in tree rings are very limited in Nepal (Sano et al., 2010, 2012). Sano et al. (2010) developed a 50-year tree-ring δ^{18}O chronology of *Abies spectabilis* growing close to the treeline (3850 m asl) in the western region of Nepal Himalaya. From the response-function analysis with ambient climatic records, they found that tree-ring δ^{18}O is primarily governed by rainfall during the monsoon season (June–September). Extreme dry years identified in instrumental weather data are also detected in the δ^{18}O chronology. Tree-ring δ^{18}O is much more sensitive to rainfall fluctuations than other tree-ring parameters such as width and density, typically used in dendroclimatology. A tree-ring δ^{18}O chronology of *Abies spectabilis* from the

Nepal Himalaya revealed increasing aridity over the past 223 years extended from 1778 to 2000 AD (Sano et al., 2012). El Nino and ENSO phenomenon can also be studied by using this technique. Though this technique gives more in-depth knowledge, due to lack of required laboratory equipments in Nepal at this moment, development of this field will depend on international collaborations.

Looking at the climate-growth response, different researchers found different response at local level; however, they got common signal in their chronologies for certain pointer year. Most of the studies have reported that climate during the spring and summer seasons play an important role for the growth of the studies species (Suzuki, 1990; Cook et al., 2003; Bräuning, 2004; Sano et al., 2005; Gaire et al., 2011; Dawadi et al., 2013; Thapa et al., 2013, 2014; Liang et al., 2014). However, in some high elevation sites winter climate also plays crucial role (Bräuning, 2004). From a study around Rara Lake, Suzuki (1990) found that rain from May to August primarily affected the tree growth and that from September to December in the previous year secondarily. Ring width of birch from Dolpo Himalayas was highly correlated with summer temperature of the summer prior to growth, whereas ring width of fir was strongly correlated with temperature during the winter before the growing season as revealed by Bräuning (2004). While from a study of *Abies spectabilis* from Humla, Sano et al. (2005) found that the ring width was correlated negatively with March–May (pre-monsoon) temperature and positively with March–May precipitation, while the minimum density was correlated positively with March–July temperature and negatively with March–May precipitation. Similarly, the birch trees growing at the timberline regions are limited by the moisture stress during spring season or months with a strong positive relationship with precipitation and negative relation with temperature of the same seasons (Dawadi et al., 2013; Liang et al., 2014).

Wood anatomy can also act as an indicator of environmental factors; however, studies on wood anatomy in dendrochronology were not yet conducted in Nepal. No study was found in Dendroseismology, Dendrogeomorphology, Dendroentomology, Dendrohydrology and Dendroglaciology, though these fields also have huge potential in Nepal.

2.3.6.5 Prospects and challenges of future tree ring studies in Nepal

In Nepal, there are many opportunities for the multitude aspects of dendrochronological research. Existence of diverse forests and vegetation ranging from tropical forest to temperate forest and subalpine meadows, large number of rivers and glaciers, changing land use pattern may provide good platform for diverse research in the context of climate change, its mitigation as well as adaptation on it. There are opportunities to work not only in the dendroclimatological aspect but also to link tree ring data to the cultural and landscape change. There are some scopes of future tree ring research in Nepal, including a) Further expansion of dendrochronological studies in tropical areas as well as in new thematic areas like pollution or dendrochemistry, dendroentomology, etc., b) Expansion of the temporal and spatial replications of tree rings for the study of past environmental changes, c) Study of abrupt events (avalanches, earthquakes, landslides, fires, climatic extremes) that have large impacts on society (Gaire et al., 2013).

2.4 Studies within the study area

Sagarmatha National Park (SNP) has attracted the researchers from throughout the world; however, very few studies have been carried out in other two study areas. Only relevant studies have been reviewed here.

Over 1000 studies have been carried out from the SNP area so far (EvK2CNR, 2014). However, very few studies have been carried out in the forest and biodiversity sectors in the area (Bhuju et al., 2010; Ferrarini et al., 2014; Garbarino et al., 2014).

Mainali et al. (2015) documented patterns of forest vegetative response to current climate variability for five major alpine forest communities in the central Himalayas of Nepal. Their results show that correlations differ according to vegetation type and confirm that both precipitation and temperature affect monthly NDVI values, though more significant correlations were found with temperature data. The temperature response was more consistent because at the maximum increased temperatures, there was still an ongoing increase in vegetative vigor (Mainali et al., 2015). This indicates that temperature is still the major limiting factor for plant growth at higher elevation sites. Clear increases in productivity are documented on the upper treeline ecotones, and these systems are likely to continue to have increasing growth rates (Mainali et al., 2015).

Sujakhu et al. (2013) studied the forest structure and regeneration of *Betula utilis* (D. Don) in birch forest located in Samagaun valley (3500 – 4000 m asl) of Manaslu Conservation Area (MCA). Among the four tree species recorded from the forest, *Betula utilis* was the dominant tree species in mixed and pure *Betula* forest, and *Abies spectabilis* was the co-dominant species in mixed *B. utilis* forest while *Rhododendron campanulatum* was the co-dominant species in pure *B. utilis* forest. Density of *B. utilis* increased with increase in elevation whereas density of other tree species decreased with increase in elevation. The density diameter curve of the tree population of *B. utilis* deviated slightly from the typical reverse J shaped structure and hence did not show the sustainable regeneration. In spite of higher sapling density than seedling density, the distribution of seedlings and saplings were not uniform among the sampling plots.

Many studies have been carried out in Rara National Park (RNP) focusing on Rara Lake and its biophysical environment (Terasima, 1984; Okino & Satoh, 1986; Yagi et al., 2010; Nakamura et al., 2012, 2015); however, very few studies dealing with forest and biodiversity aspect can be found. Terasima (1984) reported three new species of fishes namely *Schizothorax raraensis*, *S. macrophthalmus*, and *S. nepalensis*, which were endemic to the Rara Lake. Suzuki (1990) collected tree cores for dendrochronological study from two forest stands around Rara Lake; one dominated by *Abies spectabilis*, and the other by *Pinus wallichiana - Picea smithiana*. Result showed that rain from May to August primarily affected the tree growth and that from September to December in the previous year secondarily (Suzuki, 1990). Yagi et al. (2010) studied origin of Rara Lake and prepared its bathymetric feature. Nakamura et al. (2012) studied the Late Holocene Asian monsoon variations from the analysis of sediment from Rara Lake. They presented the first evidence of terrestrial summer monsoon wind strength changes from Rara Lake, western Nepal, based on Mn/Ti ratios, a proxy for lake stratification. Result also indicated a link between the Arabian Sea and the Himalayas, suggesting that centennial- to millennial-scale changes in wind strength occurred synchronously. Nakamura et al. (2015) presented a record of changes in summer monsoon strength during the Holocene from the analysis of sediments from Rara Lake. The study indicated that a period of prolonged weak monsoon interval at around 4 ka. The timing of onset and recovery from the event observed at Lake Rara displays similarity with changes in the Indus River discharge. This was the first record of the “4.2 ka event” i.e. weak summer monsoon, from the Himalayas based on a relatively well-constructed age model using ^{14}C dates that are not influenced by reservoir effects (Nakamura et al., 2015).

From the overall review, it was found that very few studies on dendrochronology and treeline research have been carried out in the present study areas and data gap exists justifying the significance of the present study.

CHAPTER 3

3. MATERIALS AND METHODS

3.1 Study area

This study is carried out in east (Sagarmatha National Park), central (Manaslu Conservation Area) and west (Rara National Park) parts of the Nepal Himalaya. The study area is selected inside the protected area as they are protected and less disturbed anthropogenically, and also represent the different climatic regime that prevails in the country.

3.1.1 Sagarmatha National Park

Established in 1976, Sagarmatha National Park (SNP) occupies an area of 1,148 km^2 and is extended from 2,845 (at Jorsale) to 8,848 m asl (top of the Mt. Everest) (Bhuju et al., 2007). It is the country's first national park that was included in UNESCO list of World Natural Heritage Sites in 1979 for its natural, ecological and cultural significance (DNPWC, 2015). In the north, SNP is linked with the Qomolangma National Nature Preserve of Tibet and extends to the Dudh Kosi River in the south. Most of the park area is very rugged and steep terrain cut by deep rivers and glaciers. The Gokyo lake series of the park is included in the Ramsar sites in 2007 (DNPWC, 2015). Six vegetation zones described for the Nepal Himalaya by Dobremez (1975) exist in the Park: lower subalpine, above 3,000 m asl, with forests of blue pine *Pinus wallichiana*, east Himalayan fir *Abies spectabilis* and drooping juniper *Juniperus recurva*; upper subalpine above 3,600 m asl, with birch-rhododendron forest of Himalayan birch *Betula utilis*, *Rhododendron campanulatum* and *R. campylocarpum*; lower alpine, above the timberline at 3,800-4,000 m asl, with scrub of *Juniperus* species, *Rhododendron anthopogon* and *R. lepidotum*; upper alpine, above 4,500 m asl, with grassland and dwarf shrubs; and sub-nival zone with cushion plants from about 5,750-6,000 m asl. Above this, conditions are arctic. Towards the treeline, *R. campanulatum* is generally dominant. Land cover classification shows that large area of land in the SNP is barren land (65.6%) most of it is above 5000 m asl, and less than 10% is forested area (Salerno et al., 2010). The park consists of 1074 species of flora, 25 species of mammals, 272 species of birds, eight species of reptiles, seven species of amphibians, and 30 species of butterflies (Bhuju et al., 2007; DNPWC, 2015).

3.1.2 Manaslu Conservation Area

Established in 1998 AD, Manaslu Conservation Area (MCA, Area: 1,663 km^2, IUCN Category: II) is a high mountain protected area situated in central Nepal Himalaya (Bhuju et al., 2007; DNPWC, 2015). The MCA is managed by National Trust for Nature Conservation (NTNC) of Nepal. MCA has a diverse natural resource base with sparse human population and is relatively inaccessible. MCA lies between 28° 20’ to 28° 45’N and 84° 29’ to 85° 11’E and is bordered by the Tibet Autonomous Region of China to the north and east, parts of the Gorkha district to the south, and the Manang and Lamjung districts to the west (Bhuju et al., 2007). It is home to 15 peaks higher than 6000 m asl, including the Mt Manaslu (8163 m asl), and five major lakes situated above 3000 m asl. The area includes nine bioclimatic zones ranging from the lower sub-tropic to the nival zone (Bhuju et al., 2007). More than 200 mountain plants species, 29 species of mammals, 110 species of birds and three species of reptiles have been reported from the park (DNPWC, 2015). It is the least explored protected area of the country. Local people depend on agriculture, animal husbandry and utilization of natural resources for their sustenance. Buddhism has positively contributed in protecting the forest and biodiversity (Chhetri, 2009).

The climate of the study area is monsoon dominated. The area covers 6 climatic zones, ranging from the lower subtropics to the arctic zone (Mainali et al., 2015), and includes three ecoregions: the eastern Himalayan broadleaf forests (EHBFs; 1500–3000 m); the eastern Himalayan subalpine conifer forests (EHSCFs; 3000–4000 m), and the eastern Himalayan alpine shrub and meadows (EHASMs; up to 5000 m) (Olson & Dinerstein, 2002; Mainali et al., 2015). Between 1982 and 2006 AD, these three ecoregions showed significant advancement in the start of the growing season of 0.21, 0.22, and 0.26 day/yr, respectively (Shrestha et al., 2012). Among all 13 ecoregions studied, the largest increase in the length of the growing season was observed in the EHASM, with 0.34 d/yr, and the EHSCF and EHBF by 0.33 and 0.28 day/yr, respectively (Shrestha et al., 2012). Barnekow Lillesø et al. (2005) identified 13 vegetation types in Nubri Valley of the MCA, with fir forest and birch–rhododendron forest as the most dominant in the area (Mainali et al., 2015). The study site is a mountain slope adjacent to Kalchuman Lake. With human settlements located not more than 2500 m asl, the study site is least disturbed anthropogenically. There is a dense forest in between the settlement and study sites.

3.1.3 Rara National Park

Rara National Park (RNP, established in 1976, IUCN Category: II) is a protected area in the mid-western Nepal covering parts of Mugu and Jumla districts (Bhuju et al., 2007; DNPWC, 2015). The RNP is Nepal's smallest protected area with an area of 106 km^2, and its buffer zone covers 198 km^2 (DNPWC, 2015). The park lies in between the latitude: 29.43-29.56° N and longitude: 82-82.16° E. Rara Lake (Elevation: 2,990 m, asl) is the main feature of the park as it is country's biggest lake (10.65 km^2) and included in the Ramsar site in 2007 (Bhuju et al., 2007; DNPWC, 2015). The lake drains to Mugu-Kamali River via Nijar Khola. The lake has a rich invertebrate fauna, like *Schizothorax hodgsoni*, *S. raraensis*, *S. macrophthalmus*, *S. nepalensis,* and *S. progastus* (Terashima, 1984; DNPWC, 2015). Chuchemara peak (4087 m asl) on the southern side of Rara lake is the highest point in the park (DNPWC, 2015). On the northern side, the peaks of Ruma Kand and Malika Kand frame the Rara (Bhuju et al., 2007). Climate of the area is temperate to subalpine.

The park is characterized by sub-alpine and high temperate vegetation (Bhuju et al., 2007). The park resides 1074 species of flora, of which, 16 are endemic to Nepal, 51 species of mammals, 272 species of birds (Bhuju et al., 2007; DNPWC, 2015). Common plant species include fir, pine, birch, rhododendron, hemlock, oak, juniper and spruce. The park consists of different coniferous forests. Blue pine (*Pinus wallichiana*) is predominant below 3,150 m asl, particularly around the lake where it may be mixed with oak (*Quercus semecarpifolia*), rhododendron (*Rhododendron arboreum*), juniper (*Juniperus indica*) and spruce (*Picea smithiana*) (DNPWC, 2015). Pine forest becomes increasingly mixed with spruce and fir (*Abies spectabilis*) at higher altitudes on the northern slopes of Chuchemara. Above 3,350 m asl fir is the dominant conifer, while oak and birch (*Betula utilis*) are relatively more plentiful and juniper persists as a shrub. Above 3,660 m asl, fir gives way to birch-rhododendron scrub and a narrow belt of dwarf rhododendron, which fringes the alpine grassland (DNPWC, 2015).

3.2 About the study species

Abies spectabilis (D. Don) Mirb, Himalayan silver fir, is commonly known as Gobre Salla, Talispatra or Thingre Salla in Nepali (Fig. 2a). The *A. spectabilis* is a tall evergreen tree 50 m in height; branchelets yellowish gray, brown or reddish brown, furrowed, hairy in grooves. Leaves linear, flattened, pectinately arranged, under-surface silvery glaucous, apex notched, margin incurved, parted on upper-sides of the branchlet (Ghimire et al., 2008). Female cone is dark purple to bluish, maturing to dark brown to blue-brown. It is 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). Fructification occurs in April-June, and fruits mature in October-December. It is commonly used for medicine, material, fuel and commercial purposes.

Figure 2: Photographs showing *Abies spectabilis* (a) and *Betula utilis* (b)

Similarly, *Betula utilis* D. Don, Himalayan birch, is commonly known as Bhojpatra in Nepali (Fig.2b). It is a medium-sized deciduous tree, with white or brownish bark, which peels off in very thin horizontal strips (Ghimire et al., 2008). In young shoots, leaves, and petioles are hairy. Leaves are ovate, acute, irregularly saw-toothed, and sticky when young. Male catkins are reddish, appearing on bare branches or with young leaves; female spikes solitary. Nutlets are conspicuously winged. It forms pure well as mixed forests at the upper limit of the treeline (Ghimire et al., 2008). Flowering occurs in April-June, and fruiting in August-October. It distributes in Nepal (W, C and E), Bhutan, Sikkim India, S- and E-Tibet, China. It is commonly used for medicine, fuel and commercial purposes (Ghimire et al., 2008).

3.3 Research design

The scientific research methodology was adopted to meet the objectives of this study considering the basic principles of dendrochronology. This study is based on cross-sectional and quantitative research design. Figure 3 presents the research flow chart.

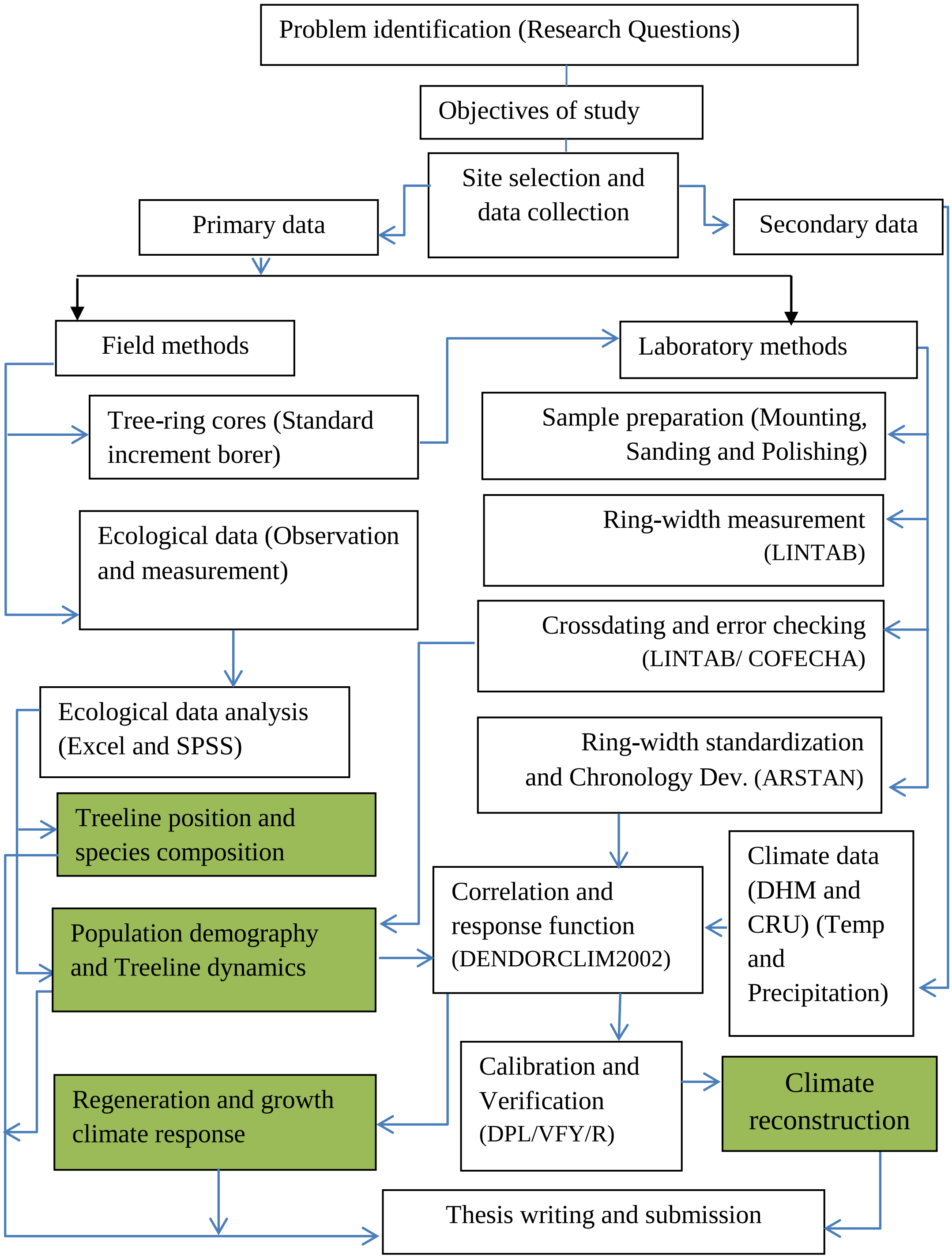


Figure 3: Research flow chart

3.4 Nature and sources of data

3.4.1 Primary data

The width of every ring in the collected tree core samples is the main primary data used in the analysis. In addition to this, other ecological data consisted information like tree name, GPS location (latitude, longitude and elevation), DBH and height and site characteristics like associated species, aspect, slope, etc. were collected as primary data.

3.4.2 Secondary data

Climatic data (temperature and precipitation) from nearby meteorological stations available in DHM and CRU grid based data were collected. Several literatures were reviewed from various sources like journals, books, websites, etc.

3.5 Field visit and data collection

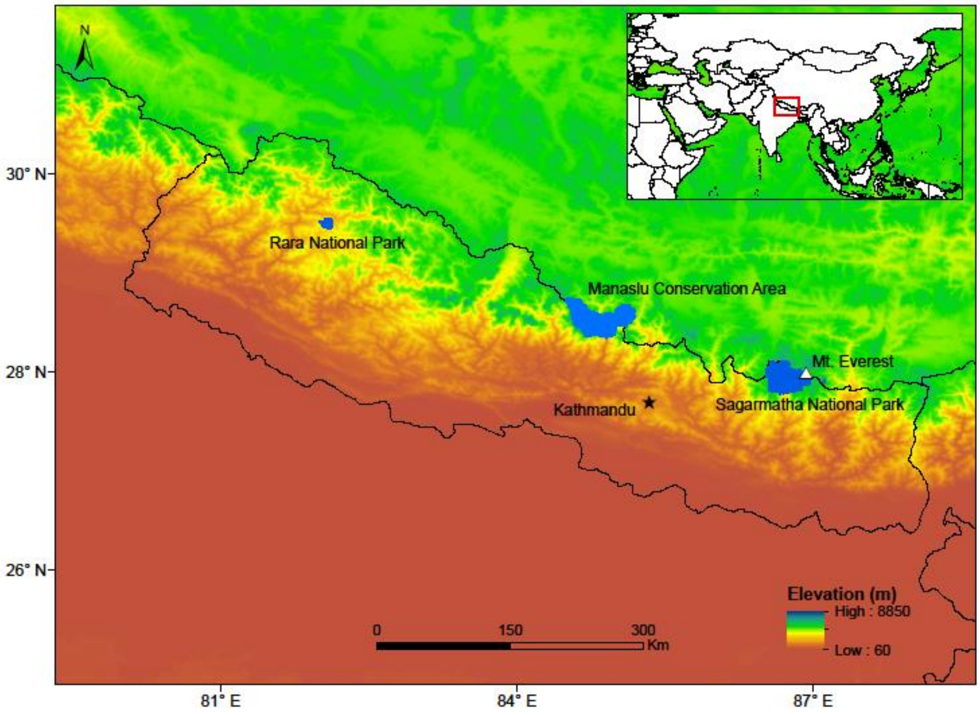


Figure 4a: Location maps of the study area and sites

This study was carried out in the treeline sites of three high elevation protected areas of Nepal Himalaya (Fig. 4a). Field work was carried out in different seasons. Field study in MCA was carried out in three expeditions: two in 2010 (May-June and

September-October) and one in 2012 (October). Fieldwork in SNP was carried out during May-June in 2012 and 2013 while in RNP was carried out in June 2014.

3.5.1 Site exploration, plot establishment and data collection

For this study, treeline is defined as the high elevation region of subalpine forest up to where 2 m tall trees can be found and the species limit is defined as the highest position to which seedlings, saplings or trees individual of tree species are present (Gaire et al., 2011, 2014). The timberline is the region of upper limit of subalpine forest with more than 30% canopy coverage.

After careful observation in transect walk at the treeline ecotones, areas having no or minimum anthropogenic disturbances were selected as sampling sites. At least two (range two to four) altitudinal transect plots (20 m wide and variable length i.e. 50 to 250 m) were marked at each sites where the treeline ecotones were as natural as possible. The plot size and replicatications was fixed based on the past experience and recommendations of past studies (Camarero and Gutiérrez, 2004; Speer, 2010; Gaire et al., 2011; Liang et al., 2011). The length of the plots was determined based on the site conditions and distribution of the plants in the ecotone to capture the site characteristics of the area in the sampling. The plots were oriented with their longer side parallel to the maximum slope and covered the current species limit and treeline ecotone.

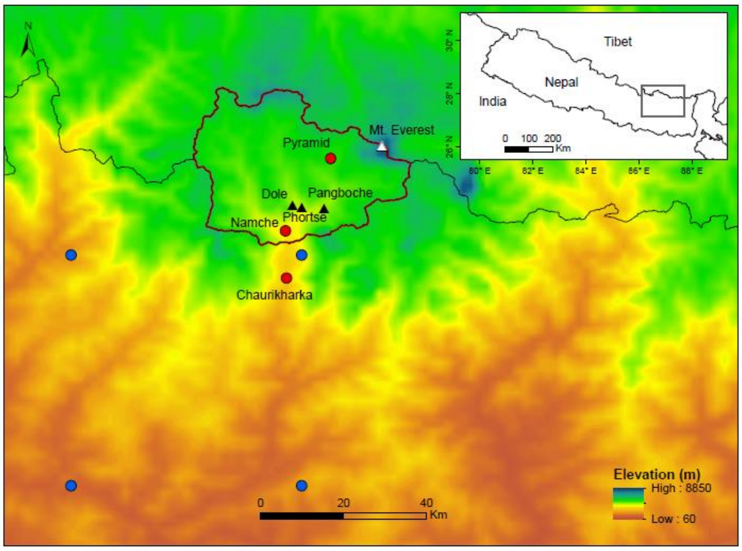


Figure 4b: Location maps of the study area and sites in Sagarmatha National Park, Nepal Himalaya. The triangles represent the sampling sites, blue circles represent CRU grid climate points and red circles represent climatic stations.

After careful observation in transect walk at the treeline ecotones of three sites (Fig. 4b) of SNP namely Pangboche, Dole and Phortse, the upper species limits of *A. spectabilis* and *B. utilis* were ascertained. Analysing the available area of mountain slope for sampling, two to four altitudinal transect plots (20 m wide and 100-190 m long) were marked at each sites of SNP. The transect plots at the Dole, Phortse and Pangboche treelines were named as D1 and D2, PH1 and PH2, and P1 to P4, respectively. The aspects of the sampling site of SNP cover north-east, north-west and north facing slopes. The ground layer of the upper reaches of most of the treelines ecotone of SNP consists of conglomerate deposits of small boulders with heavy moss cover and thin soil layer. However, towards the timberline area, there was well developed soil profile with deposition of the leaf litter and twigs.

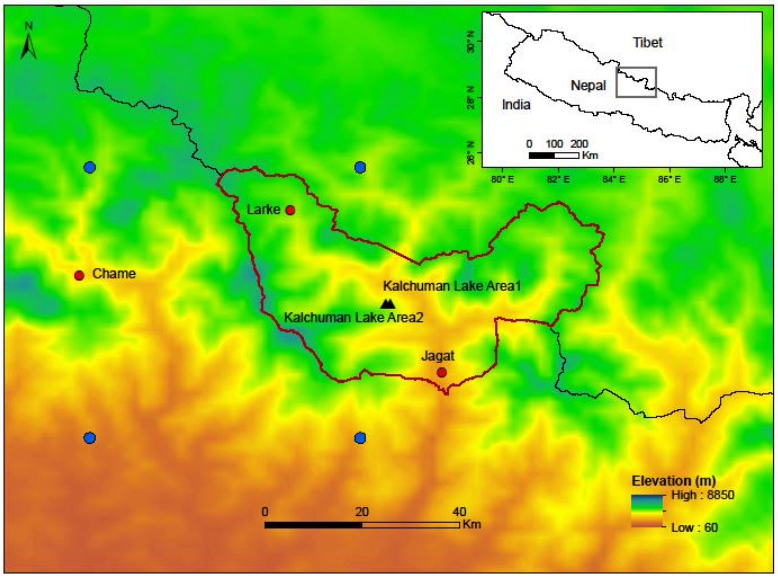


Figure 4c: Location maps of the study area and sites in Manaslu Conservation Area, Nepal Himalaya. The triangles represent the sampling sites, blue circles represent CRU grid climate points and red circles represent climatic stations.

Two altitudinal transect plots (20 m wide and >250 m long), named Transect1 (T1) and Transect 2 (T2) were marked at two sites of the treeline ecotone of Kalchuman lake area of MCA (Fig. 4c). The aspect of this area was north to north-east. T1 was above the continuous forest, while T2 was situated above the middle part of the lake. It was also assumed that the lake might hinder the dispersal of seedlings in the area. 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 anthopogon* and some herbaceous species.

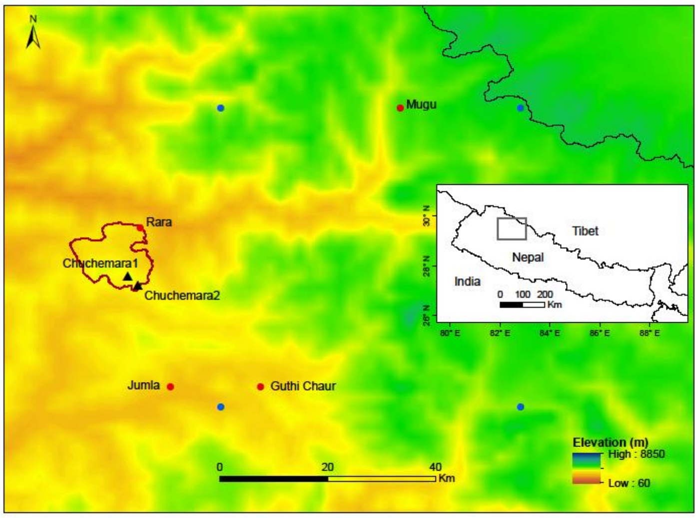


Figure 4d: Location maps of the study area and sites in Rara National Park, Nepal Himalaya. The triangles represent the sampling sites, blue circles represent CRU grid climate points and red circles represent climatic stations.

The study site in RNP was situated in Chuchemara peak area (Fig. 4d). Three transect plots (10 m wide and 50-250 m long) were established in the area. The plots were named as R1 to R3. The aspect of the area was north and north-east. The area has well developed soil profile. The treeline area was dominated by *Betula utilis* with only few *Abies spectabilis* in lower reaches, and scattered *Rhododendron campanulatum* understory. Above the treeline was open grass land with or without narrow band of *Rhododendron anthopogon* shrub scrubs.

Census counts were carried out inside each plot for *A. spectabilis* and *B. utilis*. For every individuals, their geographic location in the plot (latitude, longitude, and altitude); diameter at base (DB), diameter at breast height (DBH), height, growth form and species were recorded. Location was measured using GPS (Garmin e-trex, ±3-5 m accuracy). Diameter was measured by using diameter tape (Kinglon, Japan). Height was measured using measuring tape and clinometer and vertex. Individual plants were categorized and enumerated into three height classes: trees (> 2 m), saplings (0.5-2 m) and seedlings (< 0.5 m), following Wang et al. (2006) and Kullman (2007). The branch whorls of each *A. spectabilis* seedlings and saplings were counted to estimate their age.

3.5.2 Tree core and cut-stump collection

Tree cores were collected using an increment borer (Haglof, Sweden) following the standard procedure (Fritts, 1976; Cook & Kairiukstis, 1990; Schweingruber, 1996; Speer, 2010). The cores of *A. spectabilis* were collected from the base of each individual, and from breast height (1.3 m) of some large individuals. One to two cores per tree was collected. In case of *B. utilis*, cores from representative sample trees incorporating different size classes were collected from base level, as well as from both base and breast heights for some large trees. Some larger and old trees of *A. spectabilis* and *B. utilis* growing outside of the plots were purposively selected and cores were collected from breast height for growth-climate response analysis. A total of 1025 tree-core samples were collected (Table 2). A total of 317 cores and cut-stump samples (218 *A. spectabilis* and 99 *B. utilis*) were collected from MCA (Table 2). Similarly, 34 cut-stump samples from seedlings and saplings of *A. spectabilis* were also collected from the root collar section. In case of *B. utilis*, 11 cut stumps samples of saplings were collected from both base and breast height in order to check the age required to reach breast height. This difference in age between two heights was used to correct the time required to reach coring height. A total of 230 (110 *A. spectabilis* and 120 *B. utilis*) core samples were collected from RNP, and 478 core samples (255 from *A. spectabilis* and 223 from *B. utilis*) were collected from SNP. The sample depth of the collected tree cores is representative and sufficient for dendroclimatic study and statistical analysis (Fritts 1976; Cook & Kairiukstis, 1990). Collected core and cut stump samples were taken to the Dendro-lab of Nepal Academy of Science and Technology (NAST) for laboratory analysis.

Table 2: Tree cores samples collected from study area

Species	**Number of cores**			
	RNP	**MCA**	**SNP**	**Total**
Abies spectabilis	110	218	255	583
Betula utilis	120	99	223	442
Total	230	317	478	1025

3.6 Laboratory analysis of samples

3.6.1 Processing of the samples

Collected core and cut-stump samples were prepared and analyzed using standard dendrochronological techniques (Fritts, 1976; Phipps, 1985; Cook & Kairiukstis, 1990; Speer, 2010). Collected cores were air dried for few days. After air drying, each core was mounted in the core wooden frame by using Fevicol white glue with transverse surface facing up. Then it was left for few days for drying up of the glue. After air drying, the surface of each core was cut with sharp razor blade. Then cores were sanded and polished using successively finer grades of sand paper (100 to 1000 grits size) until optimal surface resolution allowed annual rings to be visible under the microscope. Similarly, the surfaces of cut-stump samples were prepared. Then, each ring was counted under the stereo zoom microscope (Leica) and assigned a calendar year with a help of known date of formation of outer rings. The width of each ring was measured to the nearest 0.01 mm precision with the LINTAB^{TM5} measuring system attached to a PC with the TSAP-Win software package (Rinn, 2003, 2010). 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 (Fritts, 1976). Each tree ring width series were visually (looking the math graphs) and statistically crossdated (looking Gleichläufigkeit, t-values and the cross-date index-CDI) using the software package TSAP-Win (Rinn, 2003). Accuracy of crossdating and measurement were further checked using the COFECHA program (Holmes, 1983; Grissino-Mayer, 2001). Cores that were correlated poorly in COFECHA, have several breakages and very young (less than 50 yrs old) were removed from the final data set prior to chronology development. These young/juvenile cores had low year-to-year variability in growth or unusual growth trends compared to the sampled population. Similarly, cores having breakage in the several sections were also discarded from further analysis. As most of the cores were collected from the ground level, there were irregular ring patterns in many cores. More than 15 damaged cores were discarded.

3.6.2 Standardization and chronology development

The corrected ring-width data were standardized using the computer program ARSTAN (Cook, 1985; Cook & Krusic, 2013; LDEO, 2013). The ring width of most of the trees decreases by age and also stores the signals that might not be interest of the study, i.e. growth trends also called noise (Fritts, 1976). The standardization using ARSTAN removes geometric and ecological growth trends resulting from tree-to-tree competition and stand dynamics while preserving variations that are likely related to climate (Cook, 1985; Cook & Kairiukstis, 1990). Removing ecological growth trends in closed canopied forests is difficult to achieve as disturbance and competition strongly influence growth; however, it can be overcome with careful and proper selection of the detrending options (Cook & Kairiukstis, 1990).

The standardized ring width also called ring width indices (I_t) was determined by dividing the measured ring widths (W_t) by the estimated widths (Y_t). Mathematically,

$$It = Wt/Yt$$

The mean of the indices obtained of all the ring width series is 1 and the variance is relatively constant.

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. In MCA, both single and double detrendings were tried. Interactive detrending using negative exponential, linear trend or a spline of 32 yrs with a 50% frequency response cutoff preserved more common signal (Cook & Peter, 1981). For *B. utilis* cores from SNP, double detrending was performed, first using negative exponential curve and second by using cubic smoothing splines curves of 20 years with a 50% frequency response cutoff. For *A. spectabilis*, both double and interactive detrendings were tried. Interactive detrending using negative exponential, linear trend or a spline of 20 yrs preserved more common signal. In RNP double detrending was done first using a negative exponential or linear and second detrending by using a spline of 20, 32 years or 67% spline curve length of each series with 50% frequency cutoff. The detrended ring-width-index series were then pre-whitened by fitting a autoregressive modeling to remove any autocorrelation effects (Cook, 1987). After detrending, individual time series were averaged using a bi-weight robust mean function (Cook, 1985). Finally, three chronologies namely standard, residual and arstan were prepared using the corrected sample.

Various chronology statistics like mean sensitivity, standard deviation, autocorrelation, within tree correlation, between tree correlation, mean series correlation, signal-to-noise ratio (SNR), expressed population signal (EPS) and variance explained were calculated to assess the quality of the site chronologies. Chronology quality was estimated using rbar (Briffa, 1995) and expressed population signal statistics (Wigley et al., 1984).

3.6.3 Chronology characteristics related analysis

3.6.3.1 Average

The mean is the point that is closest to all values for the data set analogous to the centre of gravity. It is defined as

$$m_x = {}^{1}/_{n} \sum x_t \qquad \text{(Fritts, 1976)}$$

Where, $\sum$ is the symbol for summations of the elements following it, x_t is the ordered value. m_x = Mean

3.6.3.2 Sample variance

Sample variance, a measure of scatter of values about the mean, is calculated as

$$S_x^2 = \frac{1}{(n-1)} \sum (x_t - m_x)^2 \qquad \text{(Fritts, 1976)}$$

Where, S^2_x = Sample variance; n = Number of observation; x_t = the ordered value and m_x = Mean

3.6.3.3 Standard deviation

It is defined as the square root of the sample variance. It is easier to visualize as a measure of scatter of data values from their mean expressed in the units of the original measurements. Mathematically standard deviation is expressed as

$$SD = \sqrt{S_x^2} \qquad \text{(Fritts, 1976)}$$

Where, SD = Standard deviation; S^2_x = Sample variance.

3.6.3.4 Standard error

It is an estimation of how a particular statistic, such as mean, varies from the mean of the entire population and it is calculated as

$$SE_m = \sqrt{(S_x^2/n)} \qquad \text{(Fritts, 1976)}$$

Where, SE_M = Standard Error; S^2_x = Sample variance; n = Number of observation

3.6.3.5 Correlation coefficient

Correlation coefficient measures interdependence of association between two data sets, x_t and y_t where t represents the time dimension. The correlation coefficient is used in dendroclimatology to measure association between two time series, such as chronologies from different trees or sites, or a chronology and climatic sequence (Fritts, 1976). Pearson's correlation coefficient is the most popular correlation coefficient. Pearson's correlation coefficient between two variables (r_{xy}) is defined as:

$$r = \frac{[1/(\mathrm{N}-1)]\sum_{i=1}^{N}(x_i-\overline{x})(y_i-\overline{y})}{\{[1/(\mathrm{N}-1)]\sum_{i=1}^{N}(x_i-\overline{x})\}^{1/2}\{[1/(\mathrm{N}-1)]\sum_{i=1}^{N}(y_i-\overline{y})\}^{1/2}} = \frac{\mathrm{cov(x,y)}}{\mathrm{S}_x\mathrm{S}_y}$$

where xi, i=1,…,N and yi, i=1,…,N are time series of length N with sample means $\overline{x}$ and $\overline{y}$, and standard deviations Sx and Sy, “cov” denotes covariance. The correlation coefficient between the two data sets being compared can range from an upper value of +1, which indicates perfect and direct agreement, to a value of -1, which indicates perfect and inverse agreement. If the two data sets are completely independent or random with respect to one another, the correlation coefficient takes a zero value (Fritts, 1976).

For approximately Gaussian data, the sampling distribution of Pearson's correlation coefficient approximately follows Student's t-distribution with degrees of freedom N − 2.

The significance of the correlation coefficient can be estimated using a t statistic:

$$t = \mathrm{r}\sqrt{\frac{\mathrm{n}-2}{1-r^2}}$$

The correlation coefficient is significant if the calculated t is higher than the critical t (n–2 degrees of freedom, α=0.05).

3.6.3.6 Regression analysis

A linear dependency of y (dependent) on x (independent) is mathematically denoted as

$$y_i = a + bx_i$$

Where, a and b are regression constants/coefficients.

3.6.3.7 Mean sensitivity

Mean sensitivity (ms_x) is the measure of relative difference in width between the consecutive rings. Douglass (1936) describes this statistic as the "mean percentage change from each measured yearly ring value to the next." The average mean sensitivity for a series is calculated as (Fritts, 1976)

$$ms_x = \frac{1}{n-1} \sum_{t=1}^{t=n-1} \left| \frac{2(x_{t+1} - x_t)}{x_{t+1} + x_t} \right|$$

Where, x_t is each datum, and the vertical lines designate the absolute value (neglecting the sign) of the term enclosed by them. The denominator of the term scales the absolute values of the differences between adjacent ring widths, x_t and x_{t+1}, so that the differences are proportional to the average of the two widths. The values of mean sensitivity range from 0 where there is no difference to 2 where a zero value occurs next to a nonzero one in the time sequence (Fritts, 1976).

3.6.3.8 Signal-to-noise ratio

Signal-to-noise ratio (SNR) is an expression of the strength of the observed common signal among trees in the ensemble (Wigley et al., 1984; Cook & Kairiukstis, 1990). The SNR is defined as

$$\mathrm{SNR} = \mathrm{N}\bar{\mathrm{r}}/(1 - \bar{\mathrm{r}})$$

Where, $\bar{\mathrm{r}}$ bar is the average correlation between trees and N is the number of trees in the ensemble of standardized tree-ring indices.

3.6.3.9 Mean correlation technique

First, we should define the correlation matrix grand mean, i.e., the mean of all correlations among different cores - both within and between trees. This can be termed (Cook & Kairiukstis, 1990)

$$\bar{r}_{tot} = \frac{1}{N_{tot}} \sum_{i=1}^{t} \sum_{\substack{l=i \\ i \neq l}}^{t} \sum_{j=1}^{c_i} r_{ilj}$$

Where,

$$N_{tot} = \frac{1}{2} \left\{ \sum_{i=1}^{t} c_i \right\} \left[\left\{ \sum_{i=1}^{t} c_i \right\} - 1 \right]$$

3.6.3.10 Within tree correlation

An estimate of the within-tree signal is given by averaging correlation coefficients between series of indices from the same tree over the all trees (Cook & Kairiukstis, 1990). This within-tree signal can be denoted as

$$\bar{\mathrm{r}}_{\mathrm{wt}} = \frac{1}{\mathrm{N}_{\mathrm{wt}}} \sum_{\mathrm{i}=1}^{\mathrm{t}} \left[\sum_{\mathrm{j}=2}^{\mathrm{c_i}} \mathrm{r}_{\mathrm{ij}} \right]$$

Where,

$$\mathrm{N}_{\mathrm{wt}} = \sum_{i=1}^{t} \frac{1}{2} c_i (c_i - 1)$$

3.6.3.11 Between tree correlation

We can also calculate a between-tree signal, r_{bt} defined as the mean interseries correlation calculated between all possible pairs of indexed series drawn from different trees (Cook & Kairiukstis, 1990):

$$\bar{r}_{bt} = \frac{1}{N_{bt}} (\bar{r}_{tot} N_{tot} - \bar{r}_{wt} N_{wt})$$

Where,

$$\mathrm{N}_{\mathrm{bt}} = \mathrm{N}_{\mathrm{tot}} - \mathrm{N}_{\mathrm{wt}}$$

3.6.3.12 Mean correlation

It can be shown that r_{mt} is given by (Cook & Kairiukstis, 1990)

$$\bar{r}_{mt} = \frac{\bar{r}_{bt}}{\bar{r}_{wt} + \frac{1 - \bar{r}_{wt}}{c}}$$

Where, r_{bt} is between tree correlations, r_{wt} is within tree correlation, and c is the number of cores per tree and must be the same for a tree.

3.6.3.13 Expressed population signal

Expressed Population Signal (EPS) is the measure of adequacy of the sample depth to represent the developed site chronology (Wigley et al., 1984). The EPS greater than 0.85 generally suggests that common signal is incorporated in the ring widths. The chronology signal, expressed as a fraction of the total chronology variance, quantifies the degree to which this particular sample chronology portrays the hypothetically perfect chronology. This has been termed the Expressed Population Signal or EPS and calculated as (Briffa, 1984; Wigley et al., 1984):

$$\mathrm{EPS}\ (\mathrm{t}) = \frac{\bar{\mathrm{r}}_{\mathrm{bt}}}{\bar{\mathrm{r}}_{\mathrm{bt}}+(1-\bar{\mathrm{r}}_{\mathrm{bt}})/\mathrm{t}} = \frac{\mathrm{t}\bar{\mathrm{r}}_{\mathrm{bt}}}{\mathrm{t}\,\bar{\mathrm{r}}_{\mathrm{bt}}+(1-\bar{\mathrm{r}}_{\mathrm{bt}})}$$

EPS is formally equivalent to the *RN2* (the expected correlation between the t-series average and the hypothetical population average) derived from first principles by Wigley et *al.* (1984) for the case of one core per tree. In this instance, it is also equivalent to the percent common signal defined by Cropper (1982) as

$$\text{Percent Common Signal} = \frac{\text{SNR}}{1+\text{SNR}}$$

3.7 Climatic response of radial growth

One of the major difficulties in undertaking dendroclimatic research in Nepal relates to the paucity of long meteorological records for statistically calibrating the tree rings because most of weather stations in Nepal were only established after 1960 for precipitation and 1970 for temperature (Shrestha et al. 1999, 2000; Cook et al., 2003). Climatic data of the following stations of SNP, MCA and RNP regions (Table 3) were collected and analyzed for the available period. Available climatic data (1980-2009 AD) of the nearest stations at Chame (28° 33’ N, 84°14’ E and 2680 m asl) of Manang and Larke Samdo (28°40’ N, 84°37’ E and 3650 m asl) of Gorkha were used for MCA. The available stations data (Chaurikharka and Namche) were used in SNP. Climatic data of meteorological stations at Jumla district (Khalanga and Guthichaur), and Mugu district (Mugu and Rara) were used for RNP. Missing values in the stations data were computed by average value of the same month’s data.

Available climatic data of some of these stations are too short for response analysis. So, high-resolution (0.5° × 0.5° grid) monthly temperature and precipitation data developed by Climate Research Unit (CRU) were extracted from the climate data points of CRUts3.22 (Harris et al., 2014) using KNMI climate explorer (Trouet & Oldenborgh, 2013). Data for CRUts3.22 are available from 1901-2013, but the data of 1901–2011 was used because all sites chronology covers up to 2011 in SNP. Mean values were averaged from four grid-boxes (27.25° N, 86.25° E; 27.25° N, 86.75° E; 27.75° N, 86.25° E, and 27.75° N, 86.75° E) covering study sites and regions.

Table 3: Information about the station and CRU climatic data used in the present study

Study area	Stations	District location	Latitude Deg/min)	Longitude (Deg/min)	Elevation (m)	Duration	Parameters
SNP	Namche	Solukhumbu	27 48	86 43	3500	2000-2010	Temperature, Precipitation
	ASW1	Solukhumbu	27 58	86 05	5050	2000-2012	Temperature, Precipitation
	ASW0	Solukhumbu					Temperature, Precipitation
	Chaurikhark	Solukhumbu	27 42	86 43	2619	1960-2011	Precipitation
	CRU	SNP, MCA, RNP	27-30	82-87		1901-2013	Temperature, Precipitation
MCA	Chame	Manang	28 33	84 14	2680	1980-2009	Temperature, Precipitation
	Larke	Gorkha	28 40	84 37	3650	1980-2009	Precipitation
RNP	Rara	Mugu	29 33	82 07	3048	1988-2006	Temperature
	Mugu	Mugu	29 45	82 33	3803	1958-1999	Precipitation
	Jumla	Jumla	29 17	82 10	2300	1957-2012	Precipitation
	Jumla	Jumla	29 17	82 10	2300	1969-2012	Temperature, Precipitation
	Guthi Chaur	Jumla	29 17	82 19	3080	1976-2012	Precipitation

Before proceeding to the response analysis of tree growth and climate, the seasonality of tree growth was defined. Though studies are lacking to say exactly when the growth of selected species in Nepal Himalaya starts and terminates. Field observation and tree ring data have shown that radial growth of *A. spectabilis* and *B. utilis* at treeline sites ceases in September-October (Sano et al., 2005; Dawadi et al., 2013; Liang et al., 2014). Because climate in the preceding growing season often influences tree growth in the following year (Fritts, 1976), the influence of temperature and precipitation since June of the previous growth year until October of the current growth year was analyzed. Simple Pearson's correlation coefficients were used to quantify relationships between tree-ring chronologies and climate variables, i.e. monthly average (T_{mean}), maximum (T_{max}) and minimum (T_{min}) temperature and total monthly precipitation. Similarly, influence of seasonal climate on radial growth was also assessed for four season namely: winter (December to February, DJF), pre-monsoon (March to May, MAM), monsoon (June to September, JJAS) and post-monsoon (October to November, ON). In addition to this, influence of annual average temperature and total precipitation was also calculated.

The relationships between the tree-ring width standard or residual chronology of each species and monthly average temperatures and total precipitations were analyzed by correlation functions and response functions by using DendroClim2002 (Biondi & Waikul, 2004), SPSS and Microsoft-excel.

3.8 Population demography, regeneration and treeline dynamics

The age of *A. spectabilis* tree individuals 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 & Gutiérrez, 2004; Wang et al., 2006; Liang et al., 2011). This age estimation by counting the branch whorls 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 representative saplings and seedlings (n = 34). Age of all *B. utilis* individuals from which tree cores were not collected was calculated using age-diameter regression analysis of sampled trees.

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 & Gutiérrez, 2004; Batalori & Gutiérrez, 2008; Speer, 2010). In such correction one to five year was added for the incomplete rings. In Manaslu two samples of *A. spectabilis* were excluded from population demography due to the incomplete cores. The age-diameter analysis regression model of *B. utilis* in MCA was based on 39 sampled trees while in SNP and RNP such regression was based on 65 and 87 trees, respectively. In SNP and RNP instead of DBH, diameter at base (DB) was used in the regression.

The regeneration condition was determined by observing size class distribution (Wangda & Ohsawa, 2006; Lv & Zhang, 2012) using the number of seedlings, saplings and trees individuals. Two sample Kolmogorov-Smirnov tests were carried out to see the difference in temporal recruitment patterns between different species and sites. The treeline dynamics was analyzed by assessing spatio-temporal distribution of tree, sapling, and seedling density as well as the elevation-wide age distribution. The upper species limit or treeline expansion was studied by observing the age of each individual in the entire plot following Camarero and Gutiérrez (2004), Liang et al. (2011), and Kirdyanov et al. (2012). In order to calculate the rate of treeline or species-limit shift, the maximum elevation of live individuals and the position of the oldest individual within each transect was determined. Then, the treeline or species limit shift rate (m/yr) was calculated by dividing the change in species limit elevation (position) by the time elapsed.

$$\text{Rate of shift} = \frac{\text{Recent position - Old position}}{\text{Time difference between two positions}} \quad \text{(m/yr)}$$

(Camarero & Gutiérrez, 2004)

3.8.1 Two Sample Kolmogorov-Smirnov Test

The two sample Kolmogorov-Smirnov test is used to test whether two samples come from the same distribution. Suppose that the first sample has size m with an observed cumulative distribution function of $F(x)$ and that the second sample has size n with an observed cumulative distribution function of $G(x)$. Define

$$D_{m,n} = \max_{x} |F(x) - G(x)|$$

The null hypothesis is H_0: both samples come from a population with the same distribution. As for the Kolmogorov-Smirnov test for normality, we reject the null hypothesis (at significance level α) if $D_{m,n} > D_{m,n,\alpha}$, where $D_{m,n,\alpha}$ is the critical value.

For m and n sufficiently large

$$D_{m,n,\alpha} = c(\alpha)\sqrt{\frac{m+n}{mn}}$$

Where, c (α) = the inverse of the Kolmogorov distribution at α, which can be calculated in Excel as

$D_{m,n,\alpha}$ = KINV(α)*SQRT[(m+n)/(m*n)]

Where, KINV is defined in Kolmogorov Distribution.

3.9 Climatic response of regeneration and treeline dynamics

Same climatic data which were used for growth-climate response were used for regeneration-climate response. Before investigating the relationship between regeneration and climate, recruitment or age data were summed up across five-year intervals as the finest resolution to take into account uncertainties in age estimates and compared with monthly climate records compiled into five-year averages over the same time period (Camarero & Gutiérrez, 1999; Wang et al., 2006). To describe the climate-recruitment relationships in MCA, monthly climatic data (mean, maximum and minimum temperatures, and total precipitation) from Chame, Jagat and Larke stations were used. For SNP, monthly climatic data (average temperature and total precipitation) of CRU gridded data and precipitation of Chaurikharka station were used. For RNP, climatic data (average temperature and total precipitation) of nearby stations at Mugu and Jumla districts were used. Climatic factors limiting regeneration were identified from simple linear correlation analysis between regeneration and climatic data.

3.10 Calibration, verification and climate reconstruction

The significant correlations obtained between the ring width chronology and the climatic variables were used to develop the transfer function to reconstruct the past climate (Fritts, 1976). Transfer function is a simple regression equation developed for the months or seasons for which the significant correlation is found. In which ring width chronology developed is used as independent variable and the significant climatic variables are used as dependent variable. Thus, the transfer function is in the form:

Climate = a RW +c

Where, Climate is the targeted climatic variable to reconstruct, i.e. average monthly or seasonal temperature or precipitation, RW is the ring-width index, a and c are the regression coefficients.

Programs Microsoft excels, SPSS and R were used for regression analysis between the chronology and climate data. A simple linear regression model was used to relate tree-ring width against seasonal climate, and tested the time-stability of that model by using different calibration and verification methods (Michaelsen, 1987; Snee 1997; Meko & Graybill, 1995). Split-sample-half (Meko & Graybill, 1995) or leave-one-out cross validation technique (Michaelsen, 1987) were used, depending upon the length of available climatic data. In spilt-half validation technique, climatic data were divided into two equal halves, verification and calibration. In leave-one-out cross validation method, calibration and validation is validated by repeating the steps iteratively and in each step one observation is removed from the calibration set and apply the model to predict the omitted observation. Estimated and observed climate data were subjected to F-test of significance in order to examine the reliability of the relationship between the response variable and the set of the predictor variables. Computer programs VFY from DPL and or PC-rec were used for split-sample-half calibration and verification technique. Computer program R was used for leave-one-out cross validation analysis.

Statistics like sign test, reduction of error (RE), coefficient of efficiency (CE), and product means test (PMT) were computed for verification of the transfer function. Positive value of RE and CE of climate-growth models is taken as a basis for validity and reliability of regression model (Cook & Kairiukstis, 1990). Once the model was judged effective and stable, it was applied to reconstruct past climate for the period covered by tree-ring width chronology. The reconstruction was truncated at the point in which EPS value becomes less than threshold value of 0.85 and the tree-ring chronology is unduly influenced by non-climatic noise (Wigley et al., 1984). The reconstructed temperature and precipitation was compared against the gridded climatic data of CRU TS3.22 (Harris et al., 2014) using KNMI climate explorer (Trouet & Oldenborgh, 2013) to identify the spatial coverage of the reconstruction.

Using the significant relationships obtained from the growth-climate response analysis, climate reconstructions of the three seasons were attempted. By using the ring width chronology of *Abies spectabilis*, temperature and precipitation of March to June in western Nepal (RNP region) and temperature of May to August was reconstructed for central Nepal (MCA region) were reconstructed.

3.10.1 Analysis of climate reconstruction model

3.10.1.1 Sign test

The sign test is a simple non-parametric test of the similarity between series based on a count of the number of agreements and disagreements in sign (Fritts, 1976). Sign test was used to examine the number of agreements and disagreements between observed and estimated climatic data. For $n < 50$, a test based on the binomial distribution must be used or tabulated critical values can be obtained (e.g. Fritts, 1976). For $n > 50$, a normal approximation can be made yielding the test statistic for an α-level of 0.05, where n is the number of years in the verification period. If the number of agreements exceeds the number of disagreements by greater than that expected by chance alone, the reconstruction passes.

3.10.1.2 Reduction of error

Reduction of error compares the estimated climate with the actual observation during the calibration period and its value ranges from minus infinity to plus one (Fritts, 1976). Reduction of error (RE) is calculated using following formula

$$RE = 1 - \frac{\sum(X_i - \tilde{X}_i)^2}{\sum(X_i - \overline{X}_c)^2}$$

where $\overline{X}_c$ is the mean of the actual data in the calibration period. RE ranges from -∞ to +1.0, with a RE = 0 being no better than calibration period climatology, i.e. $\overline{X}_c$. There are no formal statistical significance tests of RE, but a RE > 0 indicates that the reconstruction is better than the calibration period mean as a hindcast, which is the lower limit reported here (Cook & Kairiukstis, 1990).

3.10.1.3 Coefficient of efficiency

Coefficient of efficiency compares estimated and observed data during the verification period (Fritts, 1976). Coefficient of efficiency (CE) is calculated using following formula

$$CE = 1 - \frac{\sum\left(X_i - \tilde{X}_i\right)^2}{\sum\left(X_i - \overline{X}_v\right)^2}$$

Where, $\overline{X}_v$ is the mean of the actual data in the verification period. Like RE, CE also ranges from -∞ to +1.0, with a CE = 0 being no better than verification period climatology, i.e. $\overline{X}_v$. Like RE, there are no formal statistical significance test of CE, but a CE > 0 indicates that the reconstruction is better than the verification period mean as a hindcast, which is the lower limit reported here (Cook & Kairiukstis, 1990).

3.11 Presentation of the results

Results were presented in an appropriate form of tables or figures. Various descriptive (Average, range, maximum, minimum, standard deviation, standard error, etc.) and inferential statistics (correlation, regression, T-test, F-test) were used to validate the results obtained in the present study.

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1 Species composition and geo-referenced treeline position

Treeline ecotones of the study areas were formed by almost the same species with slight variation between different aspects. In Pangboche of Sagarmatha National Park (SNP), the treeline was formed by *Abies spectabilis, Betula utilis, Juniperus recurva, Rhododendron campanulatum* and *Sorbus microphylla* while in Dole and Phortse of SNP *Salix* sp. has also been recorded in addition to the previous five species. The treeline of the north and north-east facing slope in Manaslu Conservation Area (MCA) were formed by four species recorded in SNP however *J. recurva* and *Salix* sp were not present. In Chuchemara, Rara National Park (RNP), the treeline was formed by *A. spectabilis, B. utilis,* and *R. campanulatum* with the dominance of *B. utilis*. The treeline in SNP and MCA are primarily composed of *B. utilis* and *A. spectabilis*, with *R. campanulatum* and *S. microphylla* forming a second tree layer. In most treeline sites of SNP and MCA, closed forests give way to a krummholz belt of *R. campanulatum* in NW- and NE-exposed slopes, which turn into alpine *Rhododendron* dwarf scrub heaths. The North and NE-exposed slope of the treeline of RNP is dominated by the *Betula utilis* with *Rhododendron campanulatum* understory. *Abies spectabilis* in these aspects is present in lower elevation than these two species. In treeline of the RNP, closed *B. utilis* forests give way directly to alpine grassland or with narrow band of alpine *Rhododendron* dwarf scrub heaths.

Table 4: Position of treeline and species line of *Abies spectabilis* and *Betula utilis* in east, central and western sites of Nepal Himalaya

Tree/species limit	***Abies spectabilis***					***Betula utilis***				
	Dole, SNP	Phortse, SNP	Pangboche, SNP	MCA	RNP	Dole, SNP	Phortse, SNP	Pangboche, SNP	MCA	RNP
Species limit (m asl)	4141	4064	4141	3984	3870	4132	4102	4115	4003	3953
Treeline (m asl)	4105	4062	4134	3907	3870	4132	4099	4115	4003	3953

Table 4 presents the position of tree and species limit of the treeline forming *A. spectabilis* and *B. utilis*. Generally, the treeline position decreases from eastern to western part of the Nepal Himalaya. From the field exploration in Dole, SNP it was found that *A. spectabilis* species limit was at 4123 m asl (27° 51’ 27.4’’ N and 86° 43’ 43.3’’ E) in D1 and 4141 m asl (27° 51’ 39.8’’ N and 86° 43’ 50.1’’ E) in D2 while *A. spectabilis* tree limit was found at 4105 m asl (27° 51’ 31.6’’ N and 86° 43’ 47’’ E) in D1and 3996 m asl in D2. In both transects the seedlings and saplings are at higher elevation than that of adult individuals. In D2 transect (190 m long) only seedling and sapling individuals of the *A. spectabilis* were recorded. *B. utilis* tree and species limit at Dole was found at same elevation i.e. 4103 m asl (27° 51’ 31.6’’ N and 86° 43’ 47’’ E) in D1 and 4132 m asl (27° 51’ 40.3’’ N and 86° 43’ 50’’ E) in D2. No *B. utilis* seedling was recorded in the plots. *B. utilis* species limit was lower than that of *A. spectabilis*. In D2, large numbers of *Sorbus*, *Salix* and *Rhododendron* individuals compared to other two species were recorded.

Abies spectabilis tree limit at Phortse, SNP was found at 4062 m asl (27° 51.46’ N and 86° 44.859’ E) in PH2 while *Abies* was absent in PH1. *B. utilis* tree and species limit was found at 4099 m asl (27° 51.483’ N and 86° 44.936’ E) and 4102 m asl (27° 51.477’ N and 86° 44.925’ E) in the PH1. *B. utilis* species limit was higher than that of *A. spectabilis* in Phortse. Irrespective of the plots, *A. spectabilis* species limit (Elv. 4141 m asl, 27° 51’ 0.5’’ N and 86° 47’ 54.6’’ E) was at higher position than its tree limit (Elv. 4134 m asl, 27° 51’ 3.7’’ N and 86° 47’ 58’’ E) in Pangboche, SNP while *B. utilis* species and tree limit (Elv. 4115 m asl, 27° 50’ 57.9’’ N and 86° 47’ 49.4’’ E) was at lower elevation than *A. spectabilis* limit. The variation in the position of the species limit and treeline of *A. spectabilis* might be due to variation in the aspect and topographic condition as well as its recent dynamics. The position of *S. microphylla* in SNP was higher than that of *A. spectabilis* and *B. utilis* in most of the sites.

In the Kalchuman lake area of MCA, irrespective of plots, *A. spectabilis* treeline was found at 3907 m asl (28° 30’ 2.2’’ N and 84° 48’ 18’’ E) and the *B. utilis* treeline at 4003 m asl (28° 29’ 52.7’’ N and 84° 47’ 45.6’’ E). The species limit of *A. spectabilis* was recorded at 3984 m asl (28° 29’ 55.7’’ N and 84° 48’ 15.6’’ E) in Transect 1 (T1) and 3955 m asl (28° 29’ 55.7’’ N and 84° 47’ 55.2’’ E) in Transect 2 (T2) and its treeline at 3907 m asl (28° 30’ 2.2’’ N and 84° 48’ 18’’ E) in T1 and 3830 m asl (28° 30’ 1.3’’ N and 84° 47’ 57.4’’ E in T2. In the case of *B. utilis* the treeline and species limit were recorded at the same elevation in both transects, i.e. at 3996 m asl (28° 29’

55.8’’ N and 84° 48’ 15.6’’ E) in T1 and 4003 m asl (28° 29’ 52.7’’ N and 84° 47’ 45.6’’ E) in T2.

Similarly, irrespective of plot, *A. spectabilis* limit was found at 3870 m asl (29° 28.068’ N and 82° 5.746’ E) and *B. utilis* treeline and species line was found at 3953 m asl (29° 27.345’ N and 82° 6.493’ E) in Chuchemara area of RNP. Looking at the form, treelines of SNP and MCA are diffuse in form, while abrupt in RNP (Fig.5).

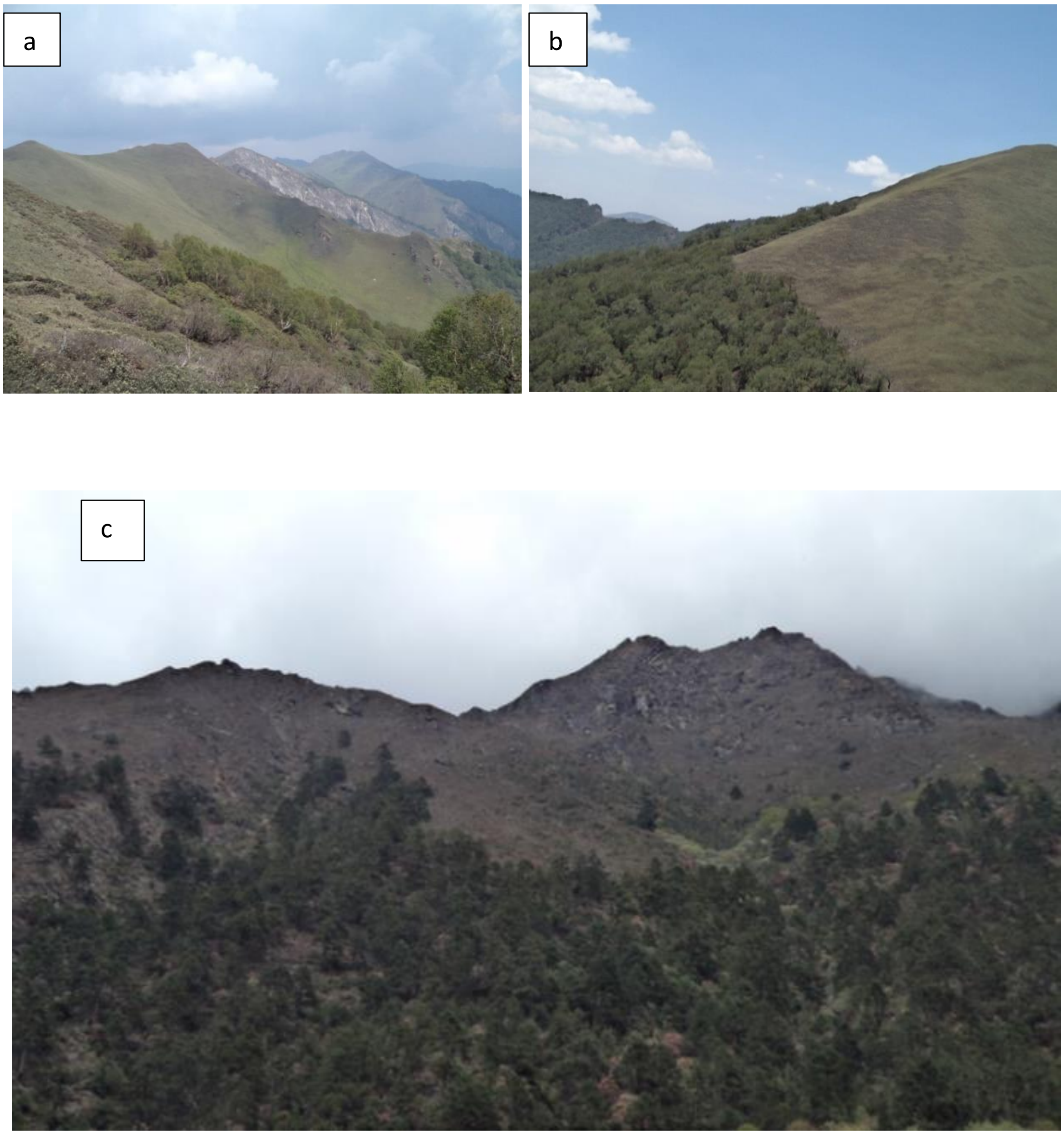


Figure 5: Treeline structures in the different sites of the Nepal Himalaya; Chuchemara (Rara National Park) (a-b), Phortse (c), Pangboche (d), Dole (e) (Sagarmatha National Park); Kalchuman Lake area (f-g) (Manaslu Conservation Area)

Figure 5: continue… Photos revealing treeline ecotones in Pangboche (d), Dole (e) in Sagarmatha National Park

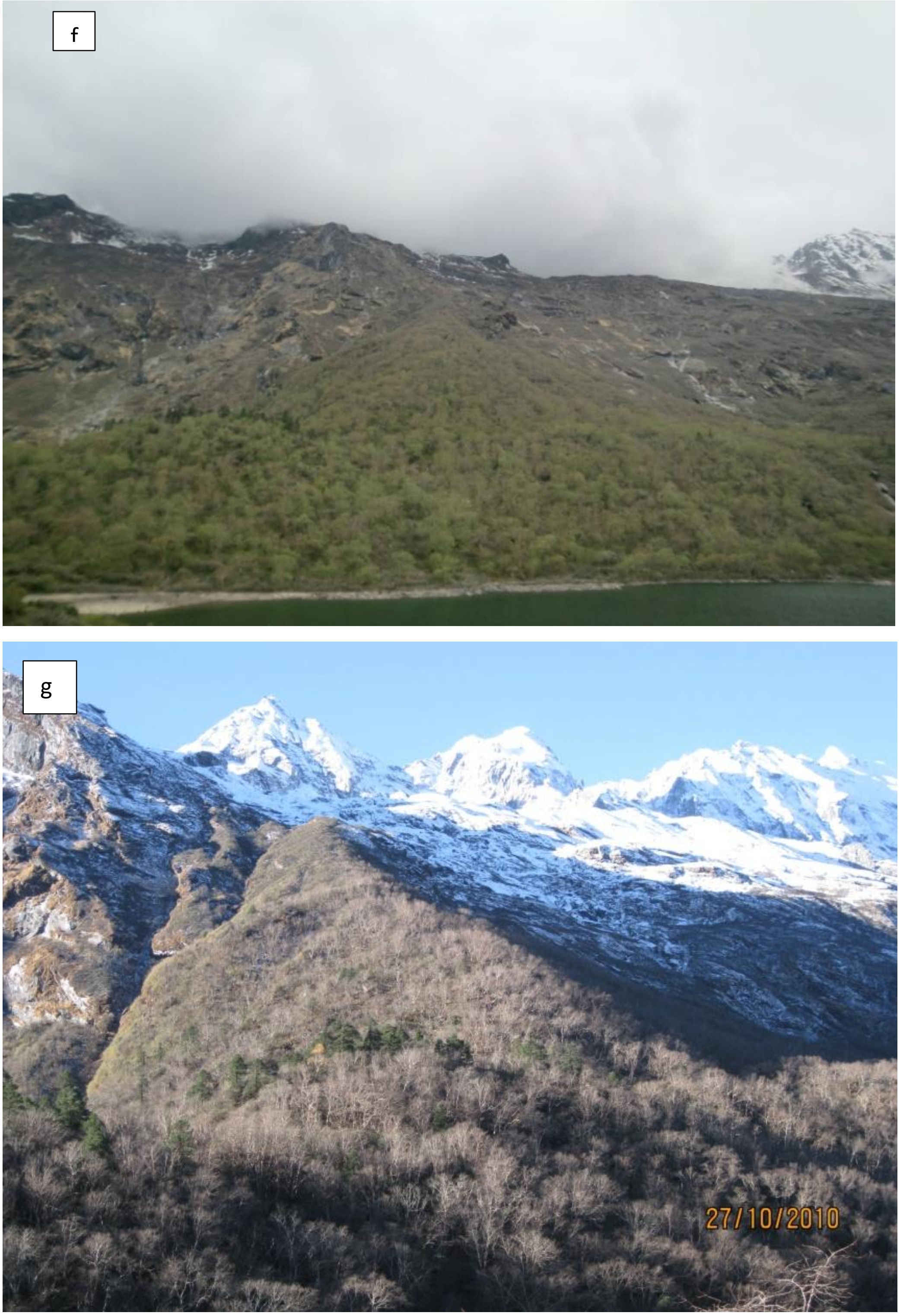


Figure 5: continue…Treeline in Kalchuman Lake area, Manaslu Conservation Area, Nepal Himalaya. Photos taken at June (Upper) and October 2010 (bottom).

The position and dynamics of the treelines are the result of the interaction of several factors including climatic (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 (Körner, 1998, 2012; Miehe et al., 2007). There are differences in altitudinal position as well as in physiognomy and species composition in Himalayan treeline ecotone (Schickhoff, 2005; Schickhoff et al., 2015). The treelines of the Himalaya are mainly formed by the *Abies* sps, *Betula utilis*, *Juniperus* sps, *Pinus wallichiana*, *Larix* sps, *Rhododendron campanulatum*, *Salix* sps, *Sorbus* sps (Schickhoff et al., 2005; Mehie et al., 2007). The tree species composition recorded in the treelines of the SNP and MCA are almost similar to the species composition recorded in treeline in similar aspects in Langtang and Lauribina in LNP and Rolwaling valley in GCA (Gaire et al., 2011; Schickhoff et al., 2015). The alpine treeline in Rolwaling valley, GCA, are primarily composed of *Betula utilis* and *Abies spectabilis*, with *Rhododendron campanulatum* and *Sorbus microphylla* forming a second tree layer (Schickhoff et al., 2015). Closed forests give way to an extensive krummholz belt of *R. campanulatum* at 3900 m asl in NW-exposed and 4000 m asl in NE-exposed, which turn into alpine *Rhododendron* dwarf scrub heaths at ca. 4000-4100 m asl (Schickhoff et al., 2015). In present study sites of SNP and MCA similar trend was observed.

In Nepal, the position of the treeline varies among eastern, central and western regions with a general decreasing treeline position while moving from east to west (Schickhoff, 2005). The treeline and species limit recorded in present study is comparable with other studies (Schickhoff, 2005; Shrestha et al., 2007; Gaire et al., 2011; Chhetri & Cairn, 2015; Schickhoff et al., 2015; Shrestha et al., 2015). Along the western slope of Mt Annapurna, the upper timberline (*B. utilis*, *R. campanulatum*) at north-facing slopes ascends to 4000-4100 m asl and to even 4400 m asl on the Nilgiri northern slope (Schickhoff, 2005). Bhuju et al. (2010) found the treeline at 4050 m asl in Pangboche of SNP region in eastern Nepal, while at the Lauribina of LNP in central Nepal it was observed at about 3900 m asl (Gaire et al., 2011; Shrestha, et al., 2015). The mean treeline position of *A. spectabilis* in LNP was located at 3824 m asl while that of *Pinus wallichiana* was located at 4067 m asl in Manang (Shrestha et al., 2015). Schickhoff et al. (2015) found some birch tree individuals growing higher than the average treeline position: in Rolwaling valley reached at 4140 m asl and in Langtang at 4215 m asl. In Barun valley of MBNP, upper treeline limit of *A. spectabilis* was at 4092, 4058 and 3960 m asl in east, south and north facing slope respectively while tree species limit was 4095, 4060, and 3964 m asl in east, south, and north, respectively (Chhetri & Cairns, 2015). On the north-facing slope in Trans-Himalayan dry valley of Manang district, central Nepal, *A. spectabilis* was found up to 4000 m asl while *B. utilis* up to treeline at 4200 m asl (Shrestha et al., 2007). Generally, the upper treeline elevations in the HKKH 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).

4.2 Forest structural parameters of treeline forming species

Table 5: Population density of the treeline forming species in treeline ecotone of east, central and western sites of Nepal Himalaya

Species	Population density (plants/ha)		
	SNP (Dole & Phortse)	MCA	RNP
Abies spectabilis	27	243	21
Betula utilis	127	192	971

The treelines investigated in present study are not monospecific but mixed. Population density varies within and between sites and species. As prime focus of this study is on *Abies spectabilis* and *Betula utilis*, density of only these two species is presented here (Table 5). The average *A. spectabilis* density (27 plants/ha; SD = 25 plants/ha) in Dole/Phortse of SNP was lower than that of *B. utilis* density (127 plants/ha; SD = 133 plants/ha) because the treeline site of the Phortse was dominated by birch trees. Density of Pangboche was not shown here because Bhuju et al. (2010) already reported plant density from there. The average density of *A. spectabilis* in MCA was found 243 (SD = 222) plants/ha and *B. utilis* was found 192 (SD = 45) plants/ha. The average density of *A. spectabilis* and *B. utilis* in RNP was found 21(SD = 37) plants/ha and 971 (SD = 559) plants/ ha, respectively. Density of plants fluctuates depending upon several biotic and abiotic conditions including site characteristics, edaphic conditions, successional stages, disturbances, community assemblages or species richness, etc (Wangda & Ohsawa, 2006). The density in Dole and Phortse is lower than in a treeline of Pangboche area (445 plants/ha) of SNP (Bhuju et al., 2010) which might be due to change in species dominance and elevation of plots in the areas. Compared among three study area, *B. utilis* density in RNP was highest which is due to the dominance and small sized *B. utilis* trees in that treeline site. Similarly, in a study along the timberline ecotones (3100-3400 m asl) in Kedarnath Wildlife Sanctuary, western India Himalaya, Rai et al. (2012) found the total tree density in the range of range of 340 to 780 trees/ha. Among the three sites, *A. spectabilis* density was highest in Kalchuman area of MCA. The density of *A. spectabilis* in Dole-Phortse in SNP region is low as compared to the density observed in other treelines like Pangboche (120 trees/ha) in SNP (Bhuju et al., 2010), Lauribina in LNP (172-277 trees/ha) (Gaire et al., 2011), and Western Himalaya of India (Rai et al., 2012). Average *B. utilis* population density in present study is comparable with that found in other treelines like Pangboche, SNP (Bhuju et al., 2010), Lauribina, LNP (Gaire et al., 2011) and Manang (Shrestha et al., 2007). In a study in SNP, Bhuju et al. (2010) found 204 stem/ha and 149 stem/ha *B. utilis* density in treeline (Pangboche) and timberline (Debuche), respectively. The *B. utilis* tree density in treeline ecotone in Lauribina region of LNP ranged from 3 to 131 tree/ha (Gaire et al., 2010). From a study along elevation gradient including treelines in Tran-Himalayan valley of Manang, Nepal, Shrestha et al. (2007) found 864 and 1207 individuals per hectare density of *B. utilis* respectively for mixed and pure *B. utilis* forest, while *A. spectabilis* density was 220 and 26 individuals per hectare. The *B. utilis* density of present study is lower than pure birch timberline but higher than mixed subalpine and timberline area of western Himalaya (Rai et al., 2012). The variation of this population density might be associated with the variation in the topoclimatic conditions, elevation of the plots and growing/succession stage of the treeline in the different areas of the Himalayas (Schickhoff, 2005; Shrestha et al., 2007; Rai et al., 2012).

4.2.1. Structural parameters at Sagarmatha National Park

Distributions of the various structural parameters like plant height, basal diameter, DBH were studied. Figure 6 and 7 show distribution of the DBH and heights of *Abies spectabilis* and *Betula utilis* tree individuals in SNP region. The average heights of *A. spectabilis* in SNP was 4.0 m (SD = 3.5 m, max = 12 m) and *B. utilis* was 5.0 m (SD

= 2.0 m, max = 12 m), respectively. The average DBH of *A. spectabilis* was 20.0 cm (SD = 12.3 cm, max = 56 cm) and *B. utilis* was 10.8 cm (SD = 7.1 cm, max = 76.0 cm). The average height of *A. spectabilis* at Dole was 1.63 m (SD = 1.73 m). Since maximum height was observed to be 5.5 m, the small average height indicates dominance of lower heights individuals' i.e. seedlings and saplings. Similarly, the average height of *B. utilis* was found 4.51 m ± 3.38 SD. This indicates a minimum presence of seedlings and saplings of *B. utilis*. The average DBH of *A. spectabilis* at Dole was 11.14 cm (SD = 5.74 cm, max = 20 cm) and DBH of *B. utilis* was 22.58 cm (SD = 19.8 cm, max = 76.0 cm). The average DBH and height of *A. spectabilis* was lower than *B. utilis* indicates that there is lack of small sized *B. utilis* individuals.

From the study it was found that the average heights of *A. spectabilis* at Phortse was 3.53 m (SD = 2.95 m, max = 8.0 m) and *B. utilis* was found 5.12 m (SD = 1.65 m, max = 7.6 m). The average DBH of *A. spectabilis* and *B. utilis* at Phortse was 17.33 cm (SD = 6.45 cm, max = 29 cm), 9.24 cm (SD = 4.61 cm, max = 28.0 cm), respectively. The average DBH and height of *A. spectabilis* was lower than *B. utilis* indicating presence of young individuals of *A. spectabilis*. The *A. spectabilis* was absent in the PH1 transect. The box plot depicted a skewed distribution of the treeline forming individuals (Fig. 6 & 7) indicating differential regeneration status of these species. Similarly, the size class distribution shows asymmetric shape indicating differential regeneration conditions in the area.

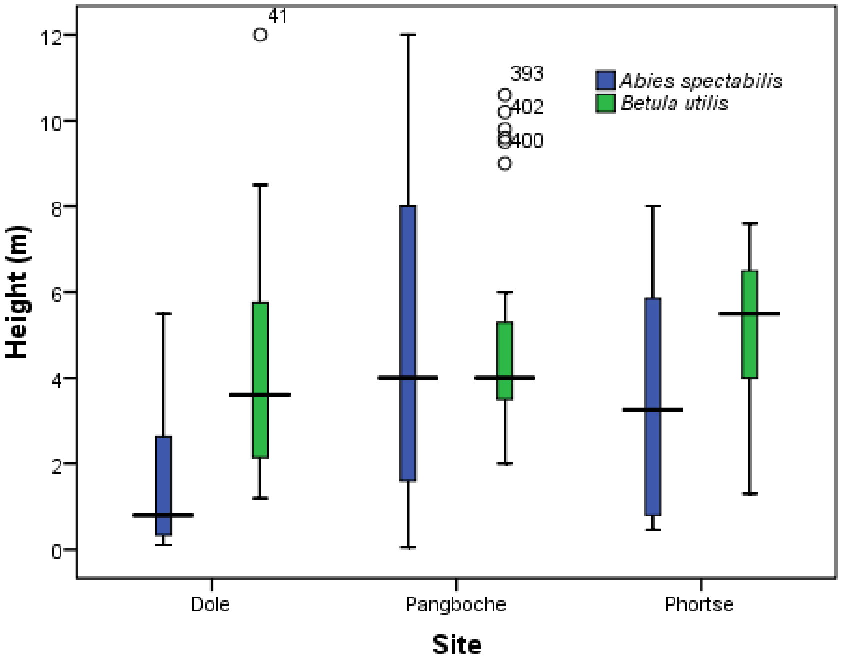


Figure 6: Box and whisker plot of height of *Abies spectabilis* and *Betula utilis* in Sagarmatha National Park, Nepal Himalaya

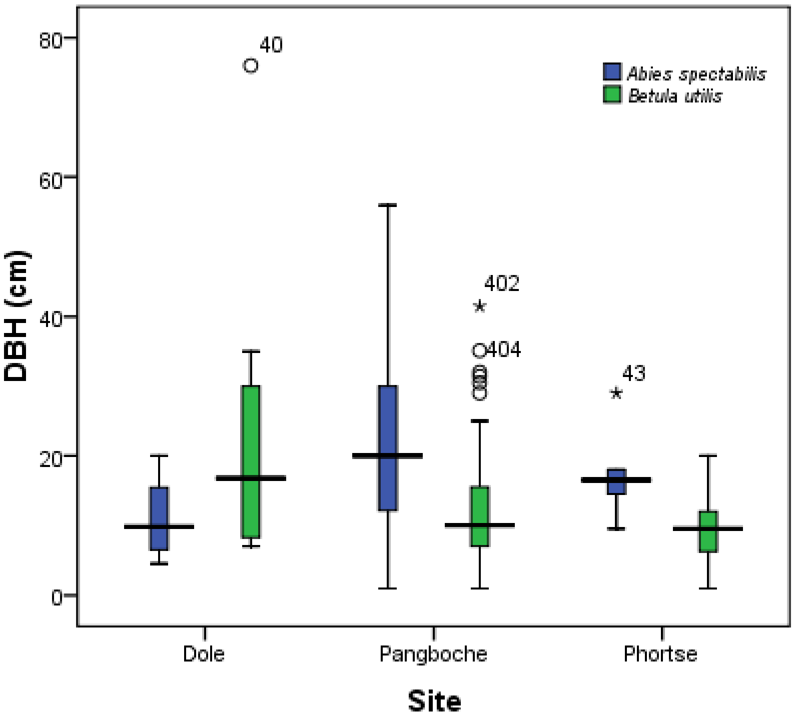


Figure 7: Box and whisker plot of DBH of *Abies spectabilis* and *Betula utilis*, Sagarmatha National Park, Nepal Himalaya

Figure 8 presents the DBH class distribution of studied species in SNP. The DBH class distribution of *A. spectabilis* in Dole and Pangboche is seen slightly inverse-J shaped, indicating continuous regeneration; however in Phortse the distribution does not have single peak. Different details exist in the plot level analysis. The DBH distribution in Phortse shows slightly unimodal distribution in the PH2 with peaks at 15-20 cm (Fig. 8); however, it was absent in PH1. The DBH distribution of *A. spectabilis* shows unimodal bell shaped distribution in D1 with peaks at 5-15 cm. Here, all individuals in D2 are smaller than breast height. In Panboche plots, unimodal to inverse-J shaped is observed.

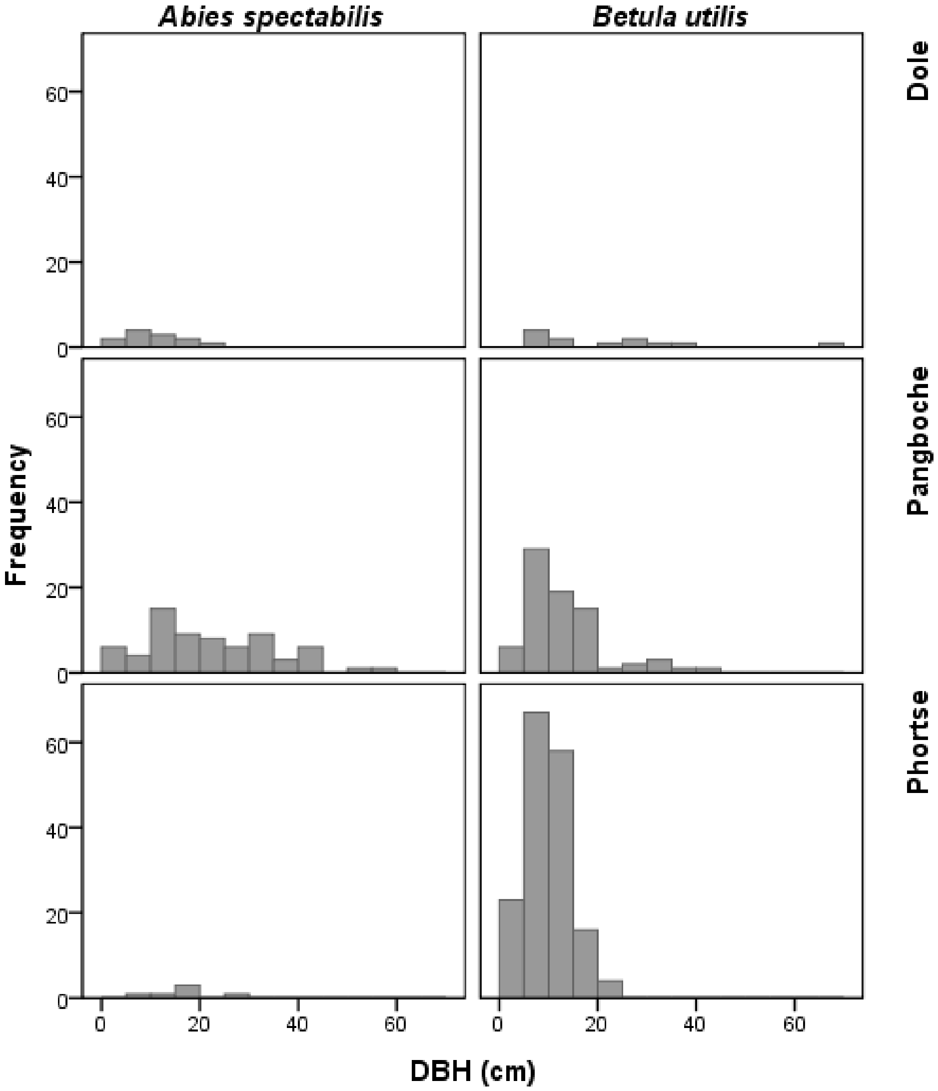


Figure 8: DBH class distributions of *Abies spectabilis* and *Betula utilis* in Sagarmatha National Park, Nepal Himalaya

As seen in Figure 8, DBH distribution of *B. utilis* is sporadic (having no peak) to an inverse-J shaped. In Pangboche and Phortse, the distribution is slightly inverse-J, but in Dole it is sporadic. DBH distribution of *B. utilis* in D1 is slightly similar to the inverse-J. However, DBH distribution of same species in the D2 shows sporadic pattern. DBH class distribution of *B. utilis* in PH1 is slightly unimodal with peak in 10-15 cm. The same species in the PH2 shows slightly an inverse-J shaped pattern indicating good regeneration compared to PH1. In Pangboche plots the distribution is unimodal bell shaped as well as an inverse-J.

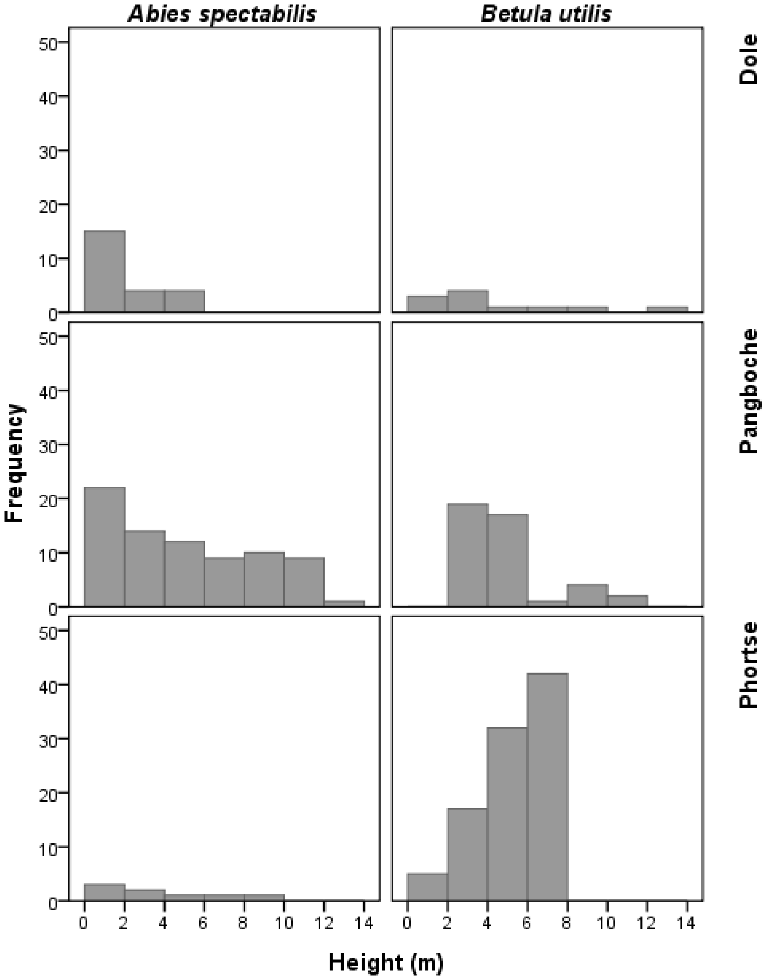


Figure 9: Height class distribution of *Abies spectabilis* and *Betula utilis* in Sagarmatha National Park, Nepal Himalaya

Height class distribution includes all individuals and shows that there is better regeneration of *A. spectabilis* than *B. utilis* in recent years with slightly an inverse–J distribution of *A. spectabilis* and bell shaped or sporadic type distribution of *B. utilis* (Fig. 9). In case of *A. spectabilis* height class 0-2 m had highest number of individuals indicating recruitment of individuals in recent years. The height class distribution of *B. utilis* shows its growing stage and site specific pattern. In plot levels distribution the height class distribution is different. From overall analysis, it seems that the recent regeneration of *A. spectabilis* is good as compared to that of *B. utilis*. There is a positive relationship between the different size parameters (Fig. 10). All the size parameters were decreased with increasing elevation in the most plots (Fig. 11).

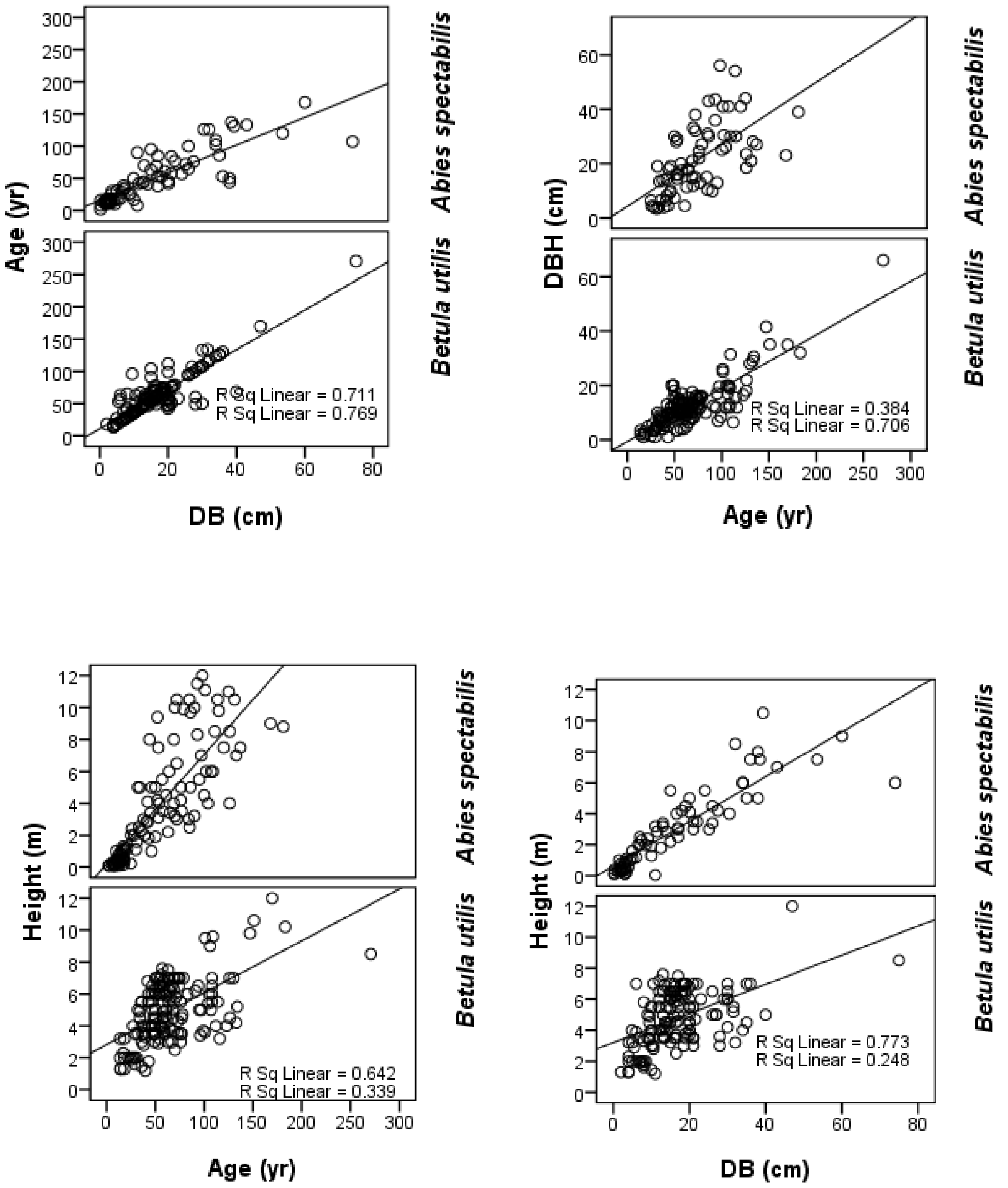


Figure 10: Relationship between various size parameters of *Abies spectabilis* and *Betula utilis* in treeline of the Sagarmatha National Park, Nepal Himalaya; Age-DB, Age-DBH, Age-height, DB-Height

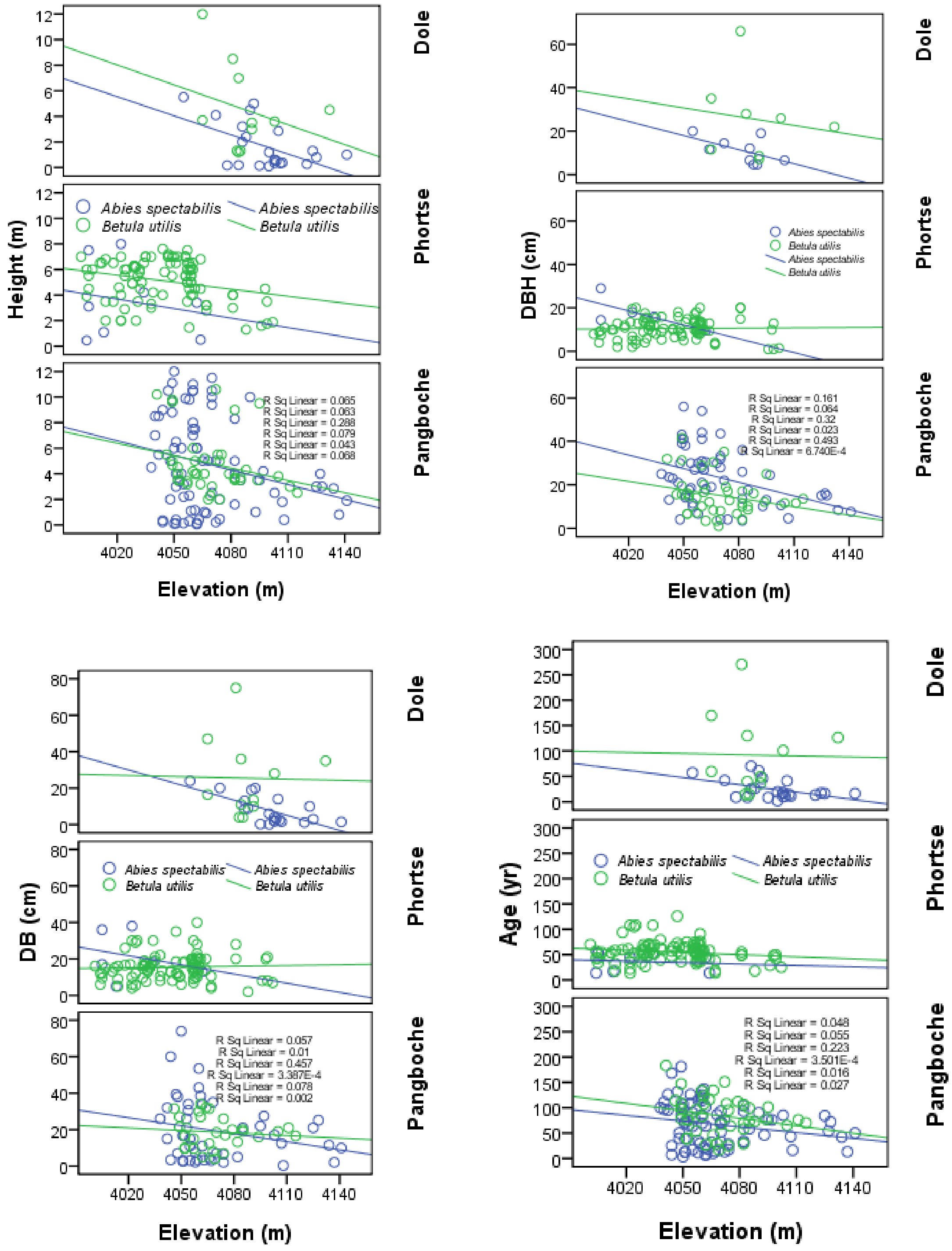


Figure 11: Elevation dependent distribution of different size parameters *Abies spectabilis* and *Betula utilis* in treeline of the Sagarmatha National Park, Nepal Himalaya

Figure 12 reveals the population age structure of *A. spectabilis* and *B. utilis* and their temporal variations. The age class distribution shows an inverse-J to sporadic pattern of distribution indicating species-specific and site-specific regeneration pattern. The age distribution of treeline forming species revealed that the recruitment history goes back to early eighteenth century in some plots; however most treeline ecotones are formed by individuals recruited in the early to middle 20th century with a majority being younger than 100 yrs. The age class distribution of *A. spectabilis* population revealed sporadic to continuous regeneration depending on the site. Age class distribution in Pangboche showed a slight peak in regeneration during 1920s, 1940s and recent decades. The young individuals recruited after 1950s dominated the total population of *A. spectabilis* in Pangboche with <50 yrs olds individuals comprising 41% of plots and 2001-2010 being dominant age class. However, the age history of *A. spectabilis* in Phortse and Dole goes back only to 1970s and 1950s, respectively, indicating that the treeline population of these two sites is formed by very young individuals.

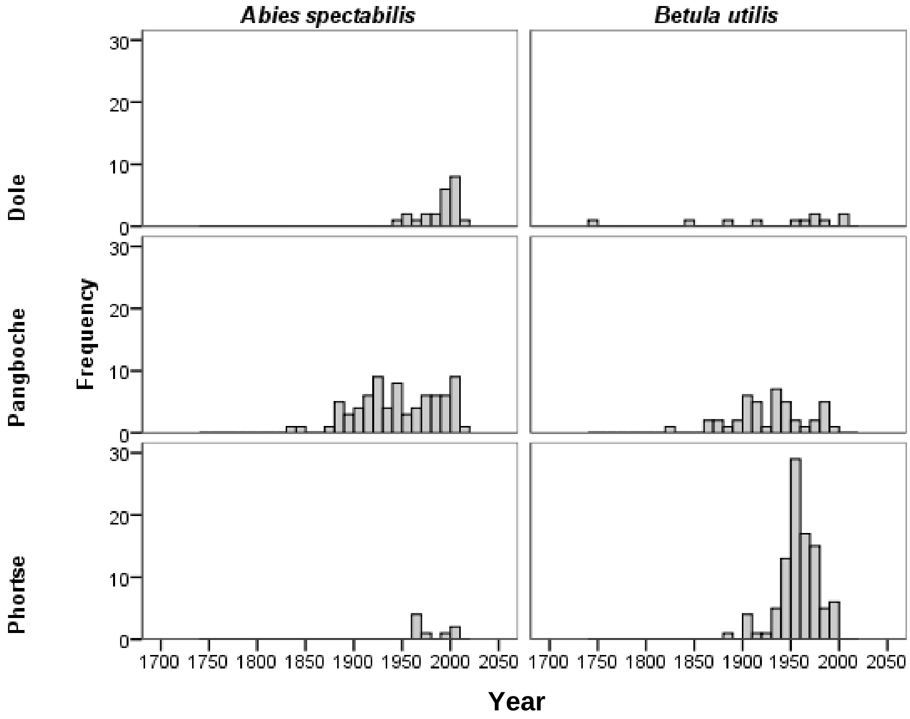


Figure 12: Age class distribution (10 year calendar year class) of the *Abies spectabilis* and *Betula utilis* in the treelines of Sagarmatha National Park, Nepal Himalaya

The age class distribution of *Betula utilis* shows sporadic to unimodal bell shaped distribution (Fig. 12). Similar to the *Abies spectabilis*, the population age of *B. utilis* goes back to 1830s in Pangboche having sporadic age class distribution with a slight peak in 1940s. After that, the regeneration of *B. utilis* is decreasing. Young (< 50 yrs) individuals comprises only 20.9% of the total population while individuals older than 100 yrs contributed 32.6% of the total population. The age history of *B. utilis* in

Phortse goes back only to 1890s; however, upper treeline (PH1) plot populations consisted of individuals all younger than 100 yrs. Age class distribution in Phortse is slightly unimodal bell shaped with peak 1960s, after that the establishment is decreasing steadily. The recruitment pattern of *B. utilis* in Dole is sporadic in nature with no single peak in regeneration.

4.2.2. Structural parameters at Manaslu Conservation Area

Figure 13 shows dispersion of the DBH and heights of the individuals in the T1 and T2 plots in MCA. The study found that the average heights of *A. spectabilis* was 1.9 m (SD = 3.6 m, max = 18.0 m) and 2.2 m (SD = 1.8 m, max = 6.5 m) at T1 and T2 respectively. Since maximum height was 18 m, the small average height indicates dominance of lower heights individuals' i.e. seedlings and saplings. Similarly, the mean height of *B. utilis* was found 6.35 m (SD = 1.7 m, max = 11.5 m) and 4.7 m (SD = 1.4 m, max = 8.0 m) at T1 and T2 respectively, indicating a minimal presence of seedlings and saplings of *B. utilis*. The average DBH of *A. spectabilis* was 22.6 cm (SD = 15.9 cm, max = 66 cm) and 10.9 cm (SD = 7.9 cm, max = 32 cm) in T1 and T2, respectively while that of *B. utilis* was found 22.2 cm (SD = 10.5 cm, max = 46.5 cm) and 13.3 cm (SD = 7.7, max = 38 cm) in T1 and T2, respectively. Since maximum DBH was observed to be 66 cm, the small average DBH indicates dominance of lower sized individuals. The average DBH of *A. spectabilis* and *B. utilis* was found to be of similar size which indicates that there is lack of small sized *B. utilis* individuals because maximum size of DBH of *A. spectabilis* was 66 cm while that for *B. utilis* was 46.5 cm.

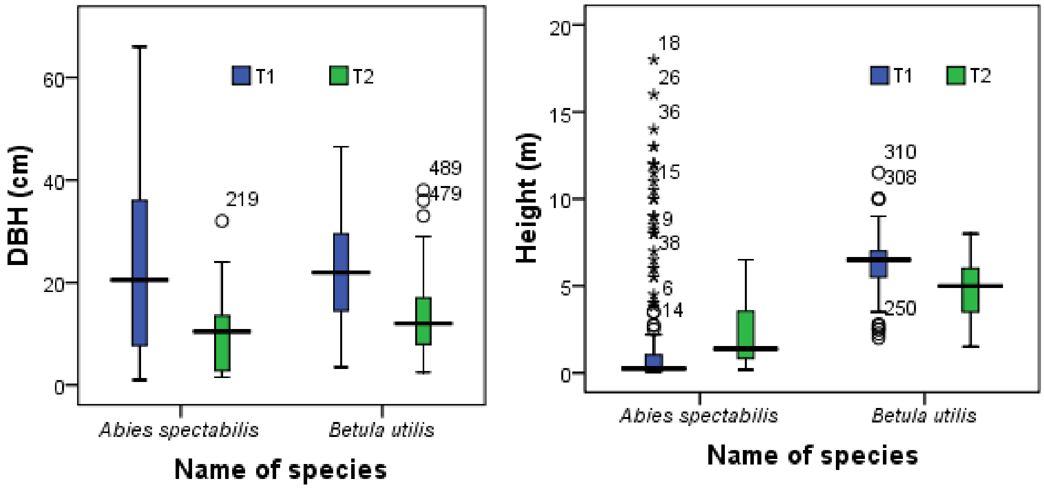


Figure 13: Box plot of DBH and heights of *Abies spectabilis* and *Betula utilis* in the treelines of Manaslu Conservation Area, Nepal Himalaya

Figure 14 presents the DBH class distribution of *A. spectabilis* and *B. utilis* in studied transects in MCA. The DBH class distribution of *A. spectabilis* shows bimodal distribution in the T1 with peaks at 0-10 cm DBH and 35-40 cm DBH classes (Fig. 14). This indicates that the population of *A. spectabilis* is composed of two types of individuals or cohorts recruited in two distinct time periods. DBH distribution in the T2 of same species had an inverse J-shape indicating continuous regeneration in the area. Distribution in T1 also shows recruitment of individuals in recent years. DBH distribution of *B. utilis* in T1 is bell shaped i.e. normal type of distribution indicating poor regeneration in the recent years. However, DBH distribution of same species in the T2 shows somewhat different pattern than that in T1. Similar trends were observed in height class distribution. In case of *A. spectabilis* height class 0-2 m had highest number of individuals indicating induced recruitment of individuals (Fig. 15). Height class distribution of *B. utilis* was unimodal bell shaped with a peak in 6-8 m class in T1 and 4-6 m class in T2.

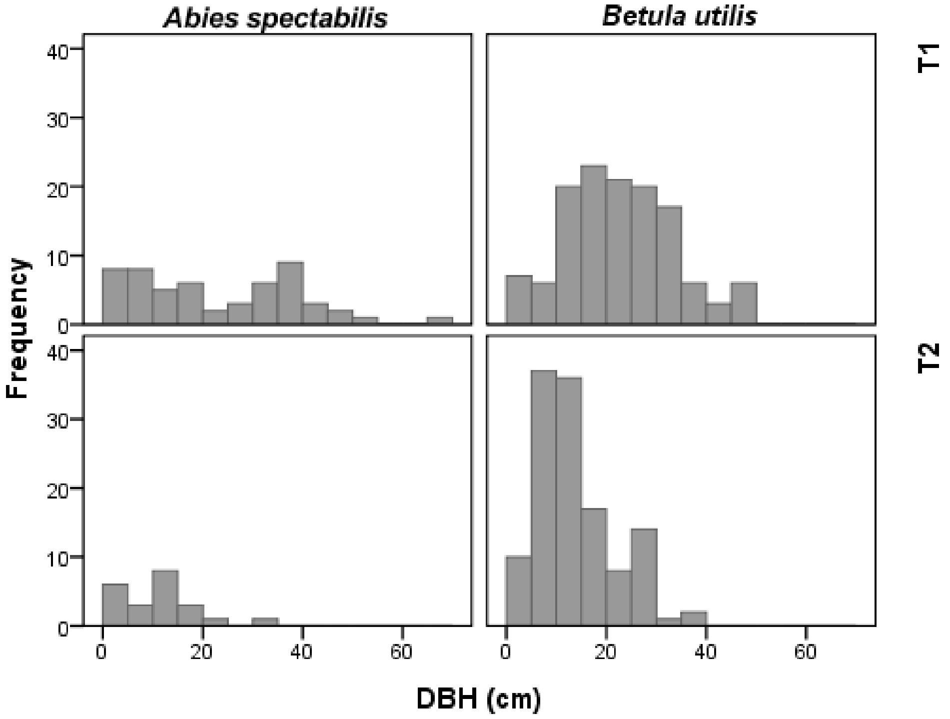


Figure 14: Distribution of DBH and height of *Abies spectabilis* and *Betula utilis* in the treelines of Manaslu Conservation Area, Nepal Himalaya. T1 and T2 are transects' name used in this study area.

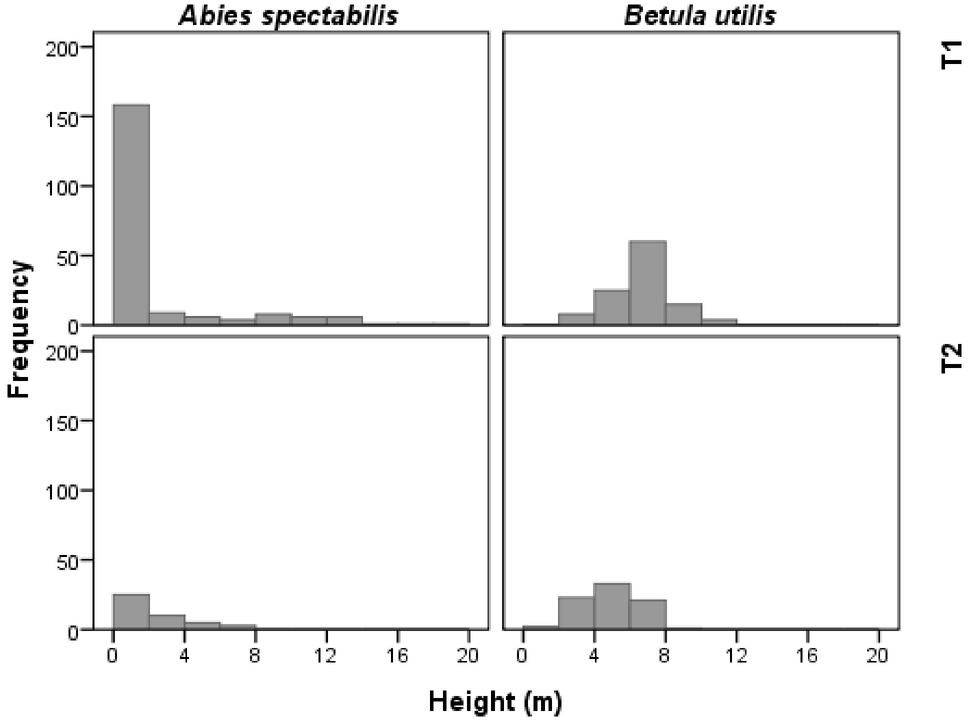


Figure 15: Height class distribution of *Abies spectabilis* and *Betula utilis* in the treelines of Manaslu Conservation Area, Nepal Himalaya. T1 and T2 are transects' name used in this study area.

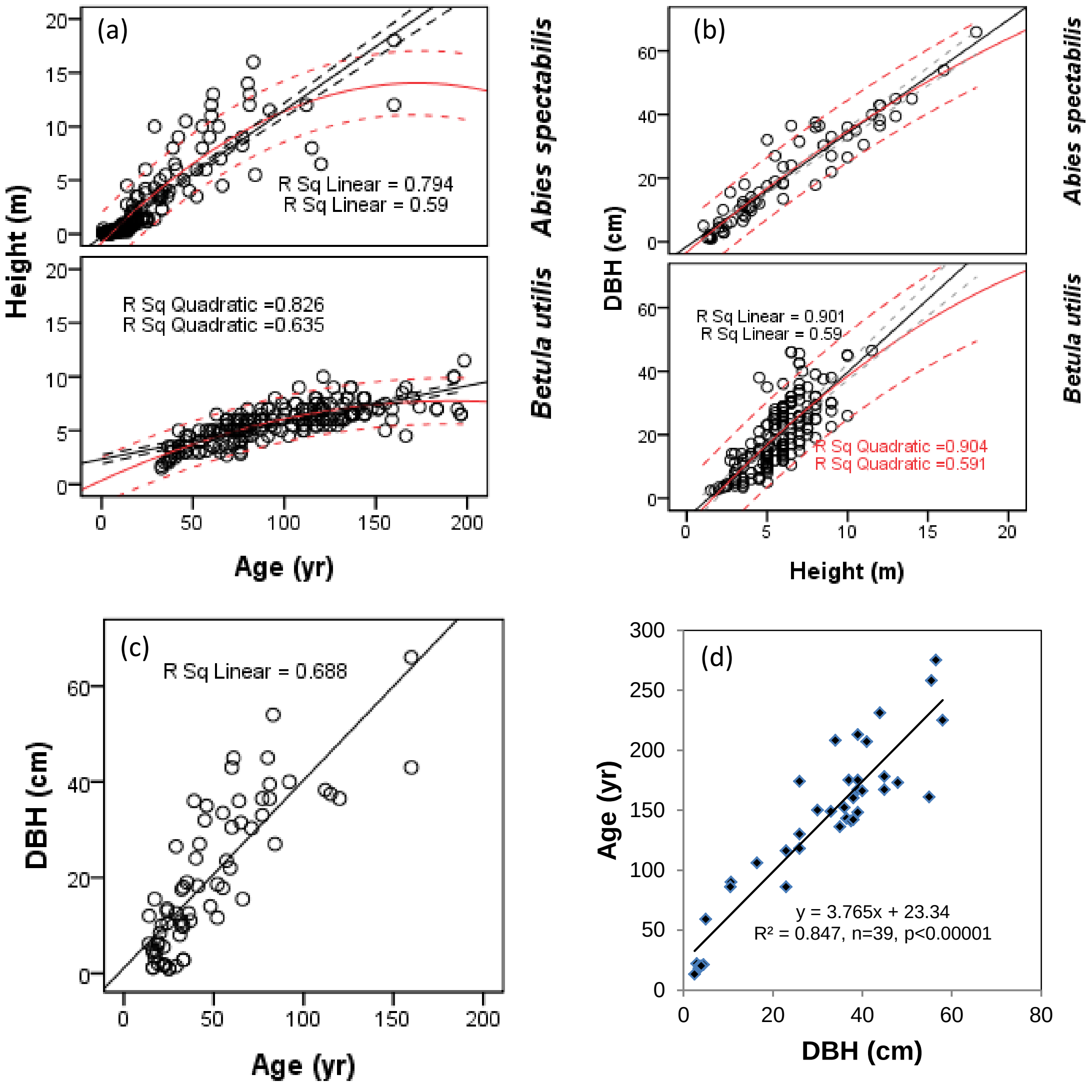


Figure 16: Relationship between different size parameters of *Abies spectabilis* and *Betula utilis* in the treelines of Manaslu Conservation Area, Nepal Himalaya; Age-height, Height-DBH, Age-DBH

There was a significant positive relationship between various size parameters like between age-DBH, age-height, and DBH-height (Fig. 16). Based on 39 trees, a regression model between DBH and age of *B. utilis* was established. The correlation between age and DBH of trees was positive and statistically significant (n = 39, r = 0.92, p < 0.00001) (Fig. 16), and this relationship was used to estimate the age of all *B. utilis* trees from which no increment cores were collected.

The elevation wise distribution of DBH and height of each individual of the *A. spectabilis* and *B. utilis* revealed that both parameters decreased with increasing elevation (Fig. 17).

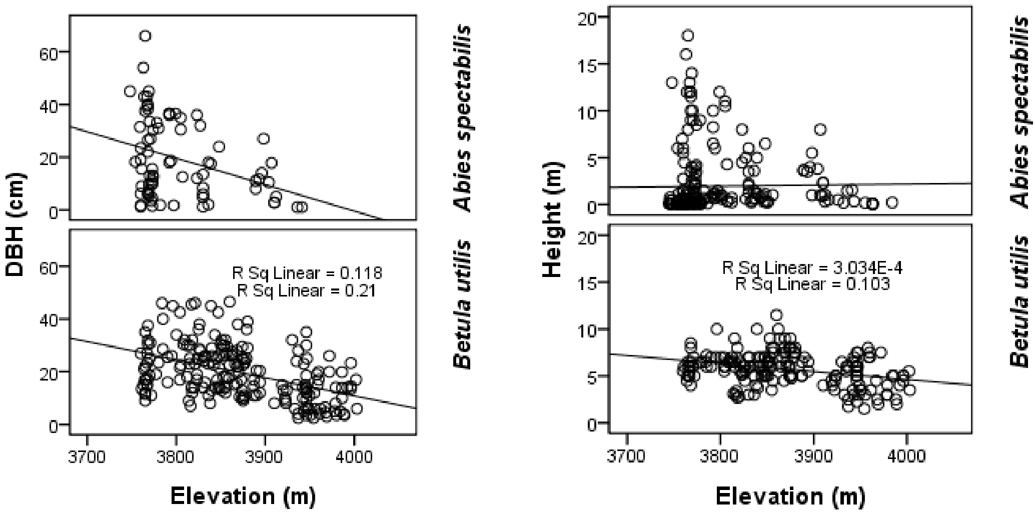


Figure 17: Elevation wise distribution of DBH and height of *Abies spectabilis* and *Betula utilis* in the treelines of Manaslu Conservation Area, Nepal Himalaya.

The age of *A. spectabilis* trees was measured by analysis of tree cores, while the age of seedlings and saplings was measured by branch whorl count and ring count method. Both age estimates (whorl count and ring count) were positively correlated ($R^2 = 0.91$, $P < 0.00001$) with a mean 1.57 ± 0.33 yrs. underestimate for the internodes or whorl count (Fig. 18). In seedlings the underestimate was 1.27 yrs. which was slightly higher for saplings. In another study, branch node method underestimates the age of seedlings and saplings by 2.4 ± 0.28 (SE) years compared to ring count method of cut stem at the root collar (Chhetri & Cairns, 2015). Hence, after corrections, branch whorl count method can give fairly an accurate age of seedlings and saplings.

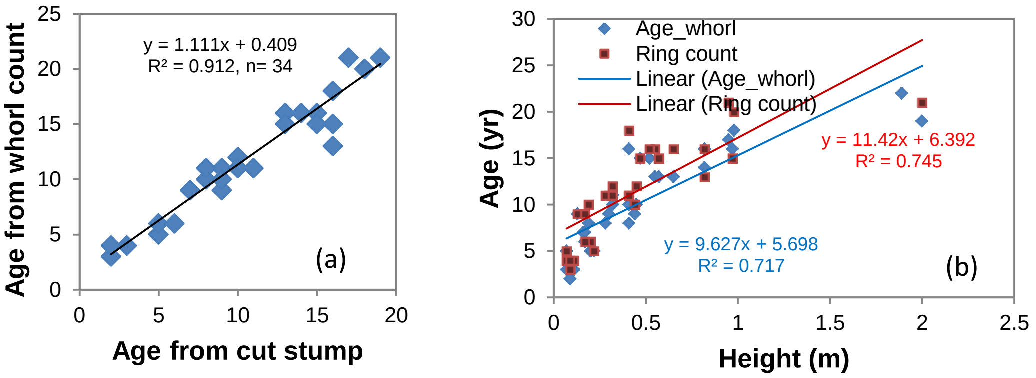


Figure 18: Relationship between the age from cutstump and whorl count of *Abies spectabilis* (a) and Height-age relationship of seedlings and saplings of *Abies spectabilis* (b) in Manaslu Conservation Area, Nepal Himalaya

Table 6 presents the descriptive statistics of age of tree species in MCA. The average age of *A. spectabilis* tree individuals was 55.5 yr (SD = 35.9 yr, max = 160 yr) and 29.2 yr (SD = 9.1 yr, max = 52 yr) in T1 and T2, respectively. The average age of all *A. spectabilis* was 18.2 yr (SD = 27.6 yr, max = 160 yr) and 22.1 yr (SD = 10.1 yr, max = 52 yr) in T1 and T2, respectively. The average age of *B. utilis* was found to be 111.3 yr (SD = 39.7 yr, max = 198 yr) and 71 yr (SD = 31.4 yr, max = 166 yr) in T1 and T2, respectively. Since maximum age was observed to be 160 years, the small average age indicates dominance of young *A. spectabilis* individuals. The average age of both *A. spectabilis* and *B. utilis* was found higher at T1 than that of T2 indicating also to lateral migration.

Table 6: Descriptive statistics of structural parameters of trees at Transect 1 (T1) and Transect 2 (T2) at the treeline ecotone of Kalchuman Lake area, Manaslu Conservation Area, Nepal Himalaya. *Includes all seedling, sapling and tree individuals.

		Height* (m)		**DBH (cm)**		**Age* (yr)**	
Species		**T1**	**T2**	**T1**	**T 2**	**T1**	**T2**
Abies spectabilis	Mean	1.9	2.2	22.6	10.9	18.2	22.1
	Median	0.24	1.38	20.5	10.5	7	19
	Std. Deviation	3.6	1.8	15.9	7.9	27.6	10.1
	Maximum	18	6.5	66	32	160	52
Betula utilis	Mean	6.35	4.72	22.2	13.3	111.3	79.0
	Median	6.5	5.0	22.0	12.0	110.5	73.2
	Std. Deviation	1.7	1.4	10.5	7.7	39.7	31.4
	Maximum	11.5	8	46.5	38.0	198	166

Age distribution of *A. spectabilis* and *B. utilis* shows the recruitment and mortality pattern over time (Fig. 19). Stand observation in the field indicate that there were more matured *B. utilis* trees than that of *A. spectabilis*. This area might be colonized by shade intolerant *B. utilis* tree at first and which were successfully invaded by the *A. spectabilis*.

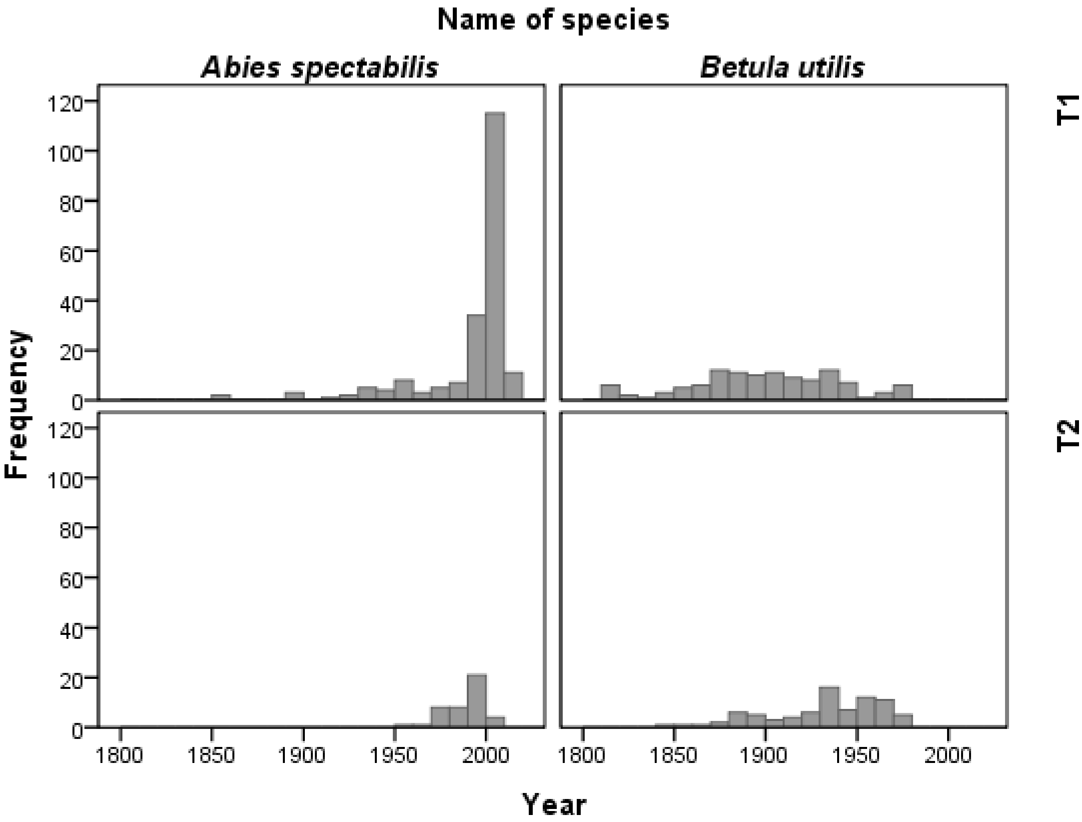


Figure 19: Age class distribution (10 calendar year class) of *Abies spectabilis* and *Betula utilis* in Manaslu Conservation Area, Nepal Himalaya. T1 and T2 are transects name used in this study area.

The age distribution of the *A. spectabilis* showed that tree could be dated back to early 1850s in the T1 (Fig. 19) and they migrated laterally and established in T2 only at beginning of 1950s. It took about a century for *A. spectabilis* to reach T2 (about 500 m horizontal distance away from T1). The population of *A. spectabilis* was dominated by young individuals comprising 89% of the population below 50 years age. The recruitment of *A. spectabilis* was slow in the 1850s which is accelerated after 1950s. This could be related to increased temperature in the area. The recruitment of *B. utilis* started from the 1820s in T1, then reached T2 in the 1840s (Fig. 19). The proportion of young population of *B. utilis* was low (13% of the population <50 yrs old) as compared to middle aged trees (42% being 50-100 yrs old) and older ones (45% over 100 yrs 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. Two sample

Kolmogorov-Smirnov test reveals that there was significant difference in temporal pattern of recruitment of two species ($\alpha = 0.05$).

4.2.3. Structural parameters at Rara National Park

Table 7: Descriptive statistics of growth parameters of *Abies spectabilis* and *Betula utilis* in the Rara National Park, Nepal Himalaya

Statistics	*Abies spectabilis*				*Betula utilis*			
	DBH (cm)	DB (cm)	Height (m)	Age (yr)	DBH (cm)	DB (cm)	Heightt (m)	Age (yr)
Mean	37.6	44.3	8.1	80.0	20.6	25.9	5.9	78.1
Standard Error	6.7	7.0	1.3	11.3	0.9	1.1	0.2	2.9
Standard Deviation	26.1	27.0	5.2	45.2	16.8	19.7	2.5	48.6
Minimum	7.0	9.0	1.0	26.0	2.0	4.0	1.0	15.0
Maximum	104.0	108.0	17.0	169.0	96.0	105.0	12.5	340.0
Confidence Level (95.0%)	23-52	29.3-59.2	5.4-11	56-104	18.8-22.5	23.6-28.1	5.6-6.2	72.5-83.7

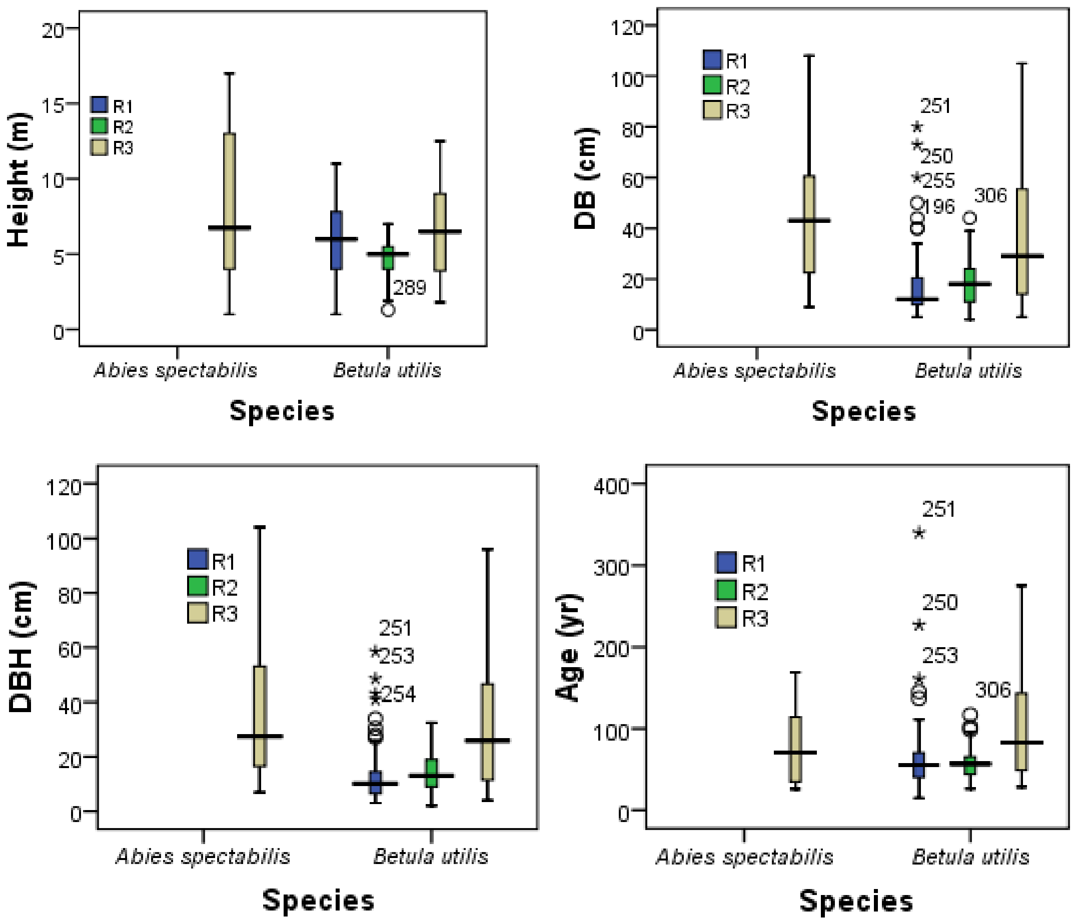


Figure 20: Box plot of size parameters of *Abies spectabilis* and *Betula utilis* in the Rara National Park, Nepal Himalaya

Table 7 presents the descriptive statistics tree species in the Rara National Park (RNP). The study found that the average DBH and heights of *A. spectabilis* was 37.6 cm (SD = 26.1 cm, max = 104.0 cm) and 8.1 m (SD = 5.2 m, max = 17.0 m) respectively. *A. spectabilis* was absent in Site 1 (R1 & R2). The average DBH of *B. utilis* was 20.6 cm (SD = 16.8 cm, max = 96.0 cm) and average height was 5.9 m (SD = 2.5 m, max = 12.5 m). All the average growth parameters of *B. utilis* were low in Site 1 (R1 & R2) compared to that at Site 2 (R3). This indicates that in Site 1 there are small trees indicating regeneration in the forest. The average age of the *B. utilis* was slightly less than *A. spectabilis*; however, maximum age of *B. utilis* was very high compared to *A. spectabilis*. The boxplot shows the skewed distribution of the size parameters (Fig. 20).

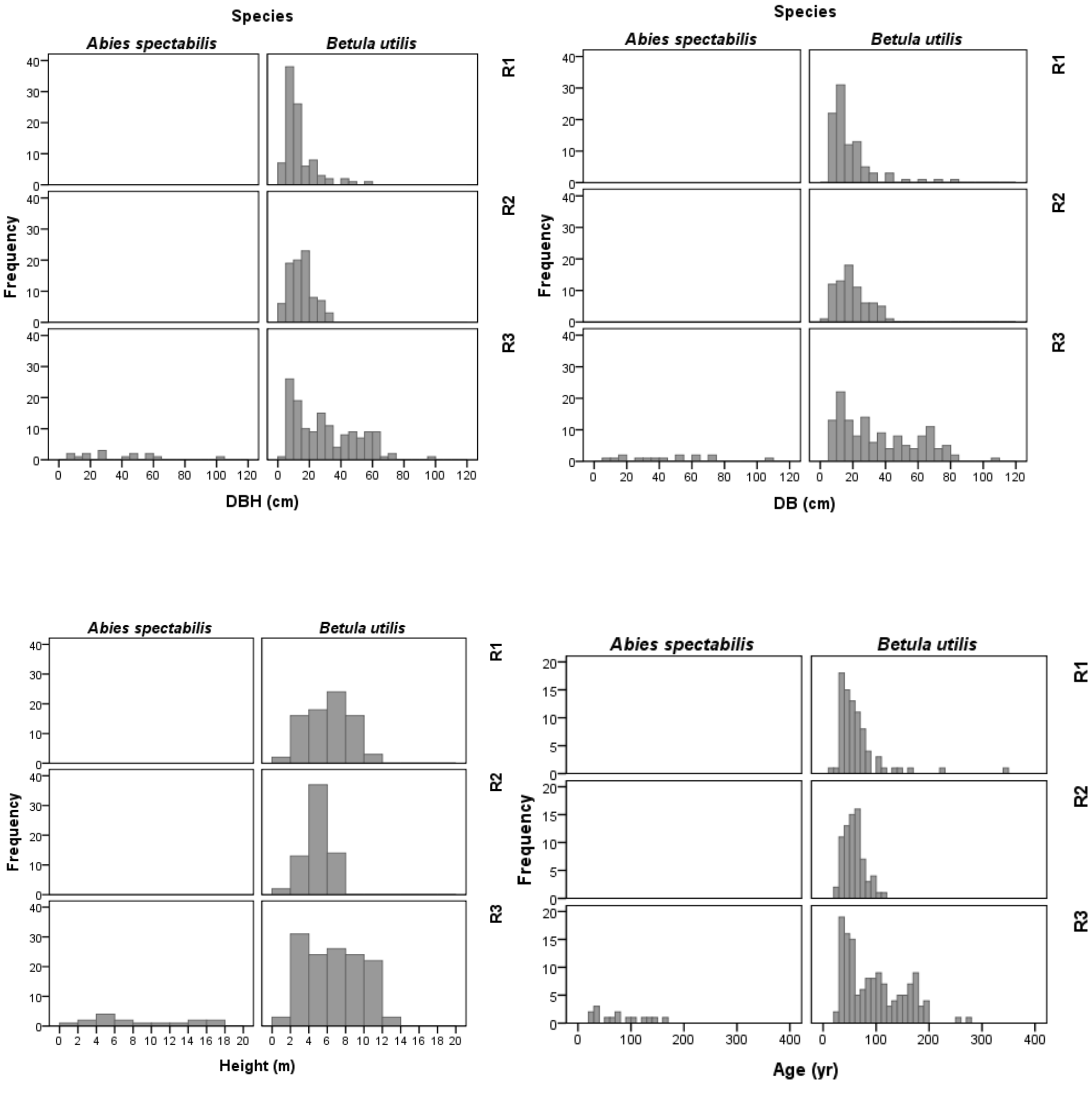


Figure 21: Size class distribution of *Abies spectabilis* and *Betula utilis* in the Rara National Park, Nepal Himalaya. R1, R2 and R3 are transects name used in this study area.

Figure 21 presents the size class distribution of major tree species in studied transects. The DBH class distribution of *A. spectabilis* does not have single peak indicating sporadic regeneration pattern. This indicates that population of *A. spectabilis* is composed of individuals recruited in different time periods. DBH distribution shows gaps in some classes indicating sporadic recruitment or some disturbances. However, the DB and DBH class distribution of *B. utilis* in both sites was almost an inverse-J shaped with peak in 5-10 cm classes indicating its continuous regeneration in the area. However, on the plot level, the distribution is slightly different. Height class distribution shows the growing stage of the trees with the majority of the individuals less than 10 m tall. The age class distribution shows different pulses of regeneration.

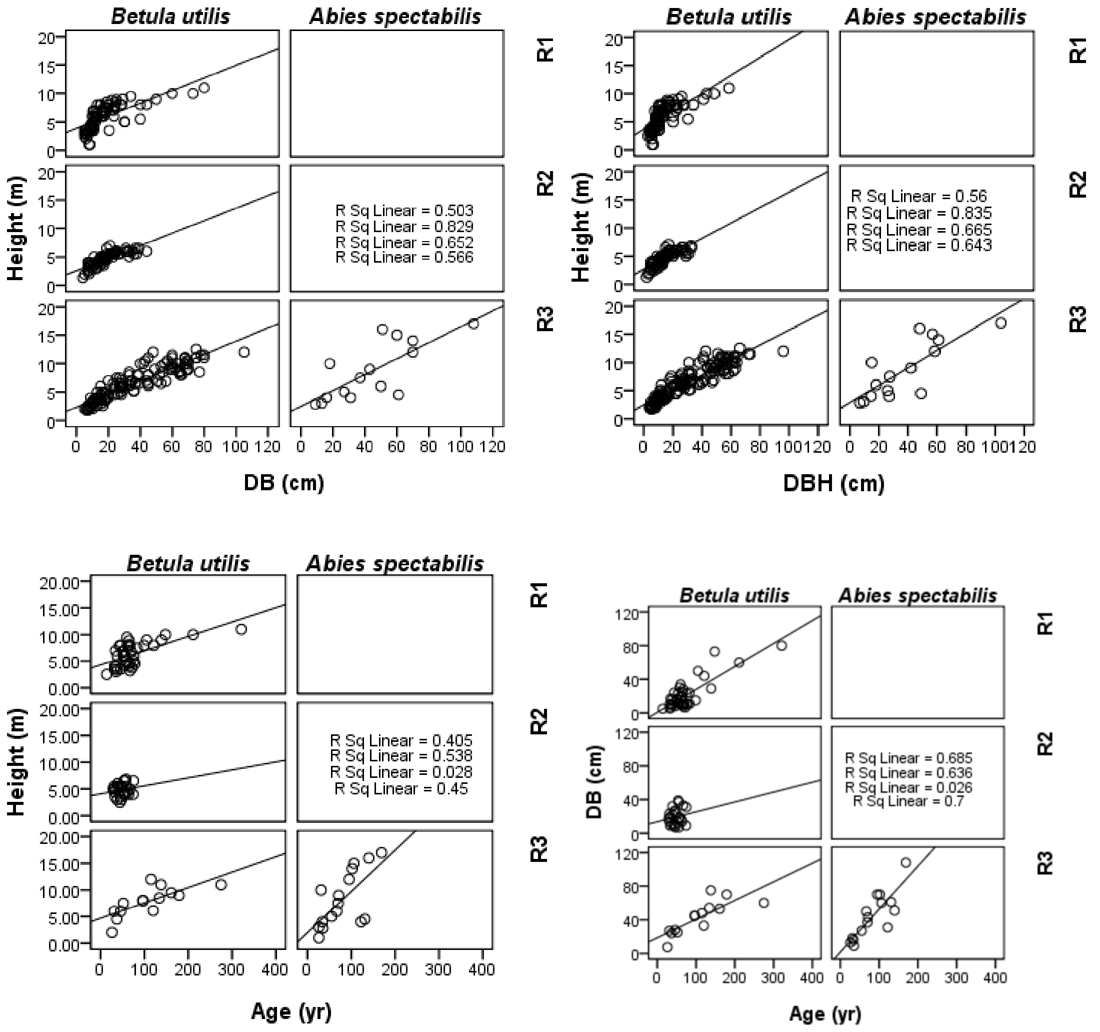


Figure 22: Relationship between the various size parameters of sampled trees of *Abies spectabilis* and *Betula utilis* in Rara National Park, Nepal Himalaya. R1, R2 and R3 are transects name used in this study area.

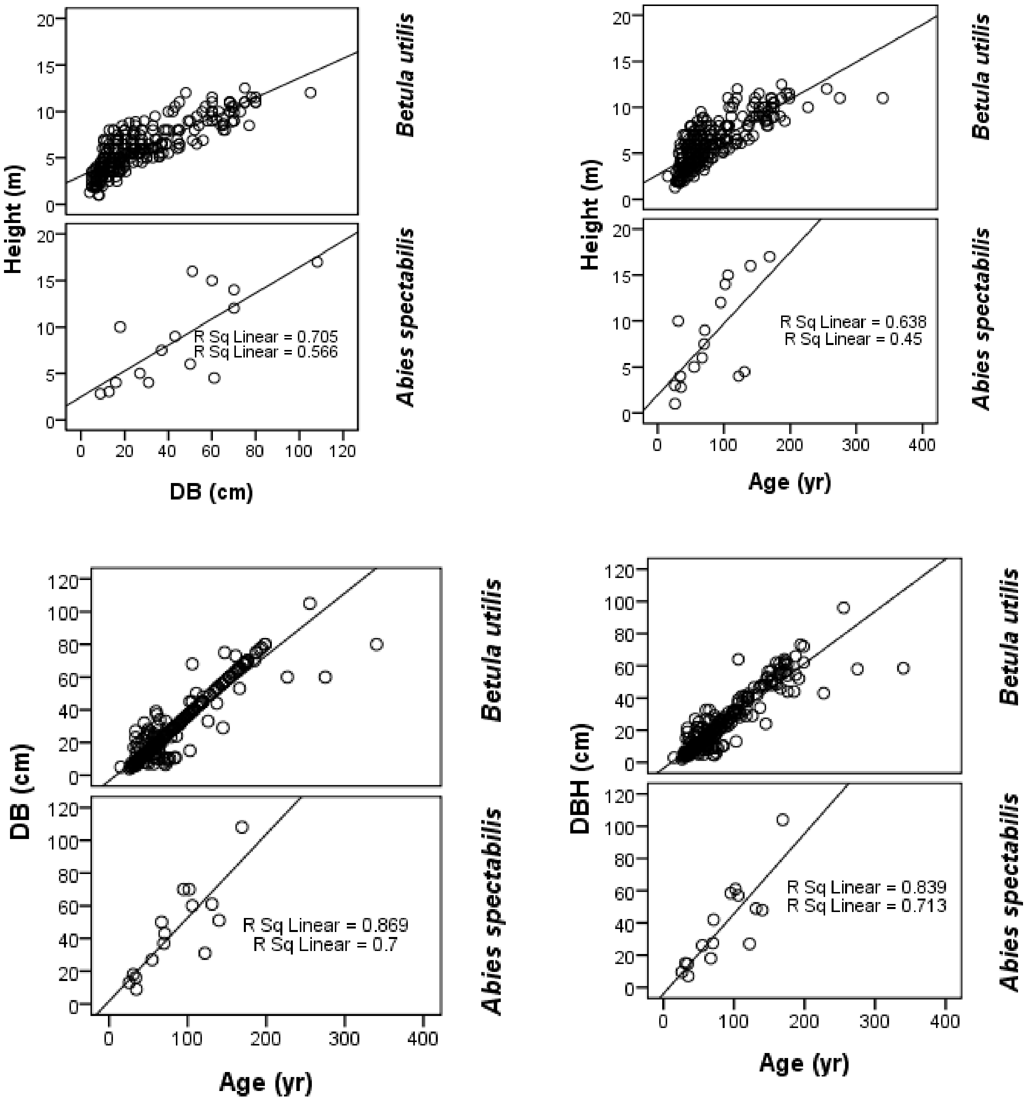


Figure 22: continue…

There was a significant positive relationship between various size parameters like between age-DBH, age-height, and DBH-height (Fig. 22). The elevation wise distribution of DBH and height of each individual of the *A. spectabilis* and *B. utilis* revealed that both parameters decreased with increasing elevation (Fig. 23).

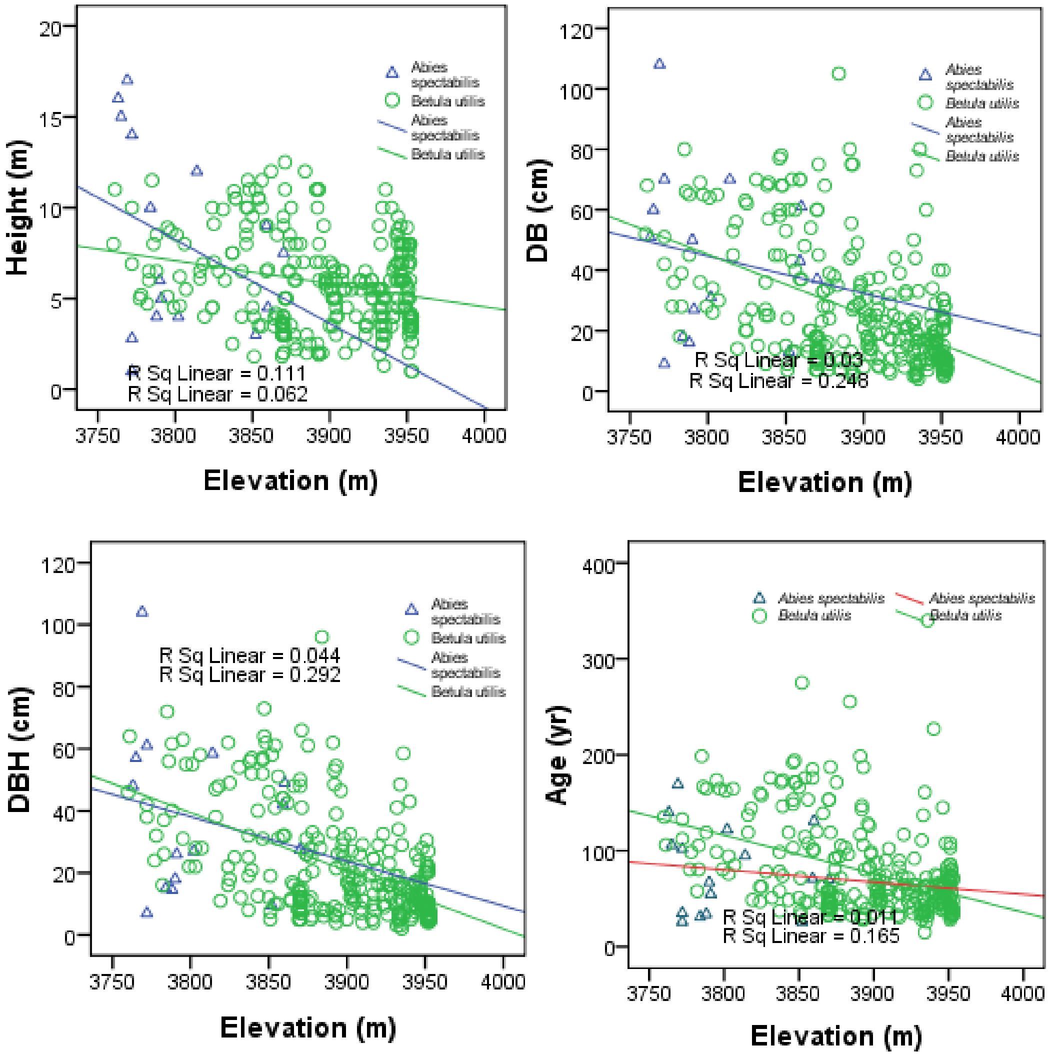


Figure 23: Relationship between the different size parameters of *Abies spectabilis* and *Betula utilis* and elevation in Rara National Park, Nepal Himalaya

Stand observation in the field indicates that there were more matured *Betula utilis* trees than that of *Abies spectabilis* (Fig. 24). Hence, this area was first colonized by *B. utilis* and followed by *A. spectabilis*. The age class distribution showed nearly an inverse-J shaped distribution of *B. utilis* indicating continuous regeneration in the treeline ecotone. Most of the *B. utilis* trees were younger than 100 years old. However, the regeneration was decreasing after 1970s. In *A. spectabilis*, there is no single peak in the distribution of age. Only few *A. spectabilis* trees were recorded in the lower reaches of the R3 plot. In other two plots, *A. spectabilis* individuals were absent. However, Kolmogorov-Smirnov test revealed that there was no significant difference in temporal pattern of recruitment of two species ($\alpha = 0.05$).

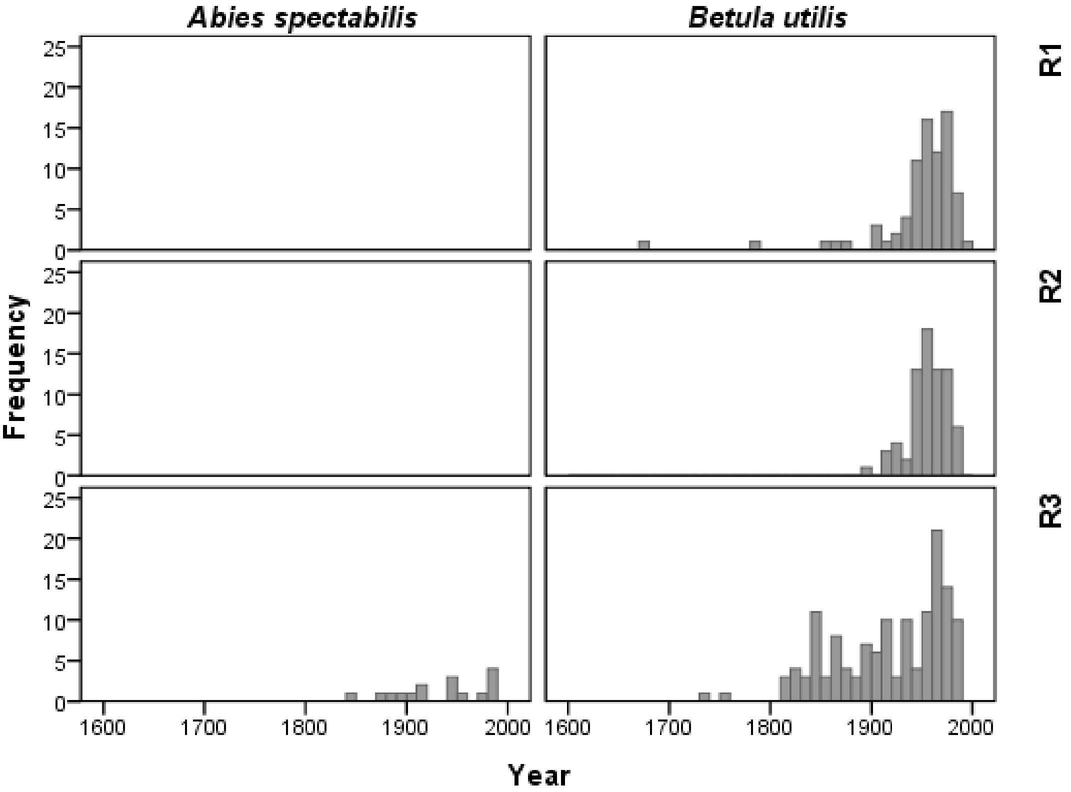


Figure 24: Age class distribution (10 calendar year class) of *Abies spectabilis* and *Betula utilis* in Rara National Park, Nepal Himalaya. R1, R2 and R3 are transects name used in this study area.

The size class distribution shows the site, species and area specific regeneration and distribution pattern. Among the three sites highest DBH of *Abies spectabilis* was found at RNP (104 cm) followed by MCA (66 cm) and SNP (56 cm). Similarly, the highest DBH of *Betula utilis* was also found in RNP (96 cm) followed by SNP (76 cm) and MCA (46.5 cm). The maximum age of *A. spectabilis* was found in SNP (181 years) followed RNP (169 years) and MCA (160 years), while maximum age of *B. utilis* was found at RNP (340 years) followed by SNP (270 years) and MCA (198 years). The inner part of trunk of an oldest *A. spectabilis* tree in the RNP was decayed and its age was based on regression of other trees. Hence, true age of this tree might be older than this. The average DBH of *A. spectabilis* in Dole and Phortse was lower than that observed in the Pangboche area of the SNP as well as treelines of the Lauribina, LNP (Gaire et al., 2011) and MCA. This might be due to the initial stage site conditions as well as low population density. However, average DBH of *B. utilis* in Dole was higher than that observed in the treeline of the Pangboche area of SNP and Kalchuman lake area of MCA and but lower than Lauribina, LNP (Gaire et al., 2010).

The size class distribution of the tree species reflects their regeneration status (Wangda & Ohsawa, 2006; Liang et al., 2011; Lv and Zhang, 2012; Rai et al., 2012). Age class distribution also represents the static life table of a species (Wang et al., 2006, Kullman, 2007; Ren et al., 2007; Qiaoying et al., 2008; Liang et al., 2011) and expresses the recruitment and mortality pattern over time. Broadly, size class distribution can be classified into three categories i.e. an inverse-J, unimodal bell or multimodal bell shaped indicating sustainable, normal, and sporadic type of regeneration (Wangda & Ohsawa, 2006). In this study, the structural parameters not only varied between the species within a plot in a site, but also between the different species, plots and sites. The age, DBH and height class distribution ranged from an inverse-J to uni to multimodal bell shaped. In MCA, the DBH class distribution of *A. spectabilis* shows a unimodal to bimodal distribution, while DBH class in most sites of SNP was inverse-J type indicating continuous regeneration. But in RNP the distribution of *A. spectabilis* was multimodal or sporadic type. The size class distribution of *B. utilis* was an inverse-J to unimodal bell shaped in most sites. However, different details exist in plot level distribution. Such kind of differences in the DBH class distribution of *A. spectabilis* and *B. utilis* have been observed in other treeline ecotones in Nepal (Shrestha et al., 2007; Bhuju et al., 2010; Gaire et al., 2011) and Indian Himalaya (Rai et al., 2012), indicating site-and species-specific regeneration condition. Similarly at the *A. spectabilis* treeline near the Everest region on the Tibetan side, Lv and Zhang (2012) observed a multimodal DBH distribution with peaks 0-10 and 30-40 cm. The height of the *A. spectabilis* can reach up to 50 m and *B. utilis* to more than 20 m during their maturity (Ghimire et al., 2008). However, average and maximum height of these two species in this study is very low. Hence, height class distribution shows the growing stage of these tree species with the dominance of the individuals in the lower height classes, as well as natural decrease in height of trees near the treelines (Holtmeier, 2009; Körner, 2012). Depending upon the site condition, successional stages and reproductive cycle of different species, the regeneration can be continuous, sporadic or episodic (Cuevas, 2002; Wangda & Ohsawa, 2006; Lv & Zhang, 2012). Studies about the seed production cycle (seed masting) of *A. spectabilis* and *B. utilis* are lacking. The size class distribution shows both continuous to sporadic type of regeneration. The gaps in some age and diameter classes in the present study indicate past disturbance events or episodic regeneration during favorable climatic periods. Similarly at the *A. spectabilis* treeline near the Everest region on the Tibetan side, Lv and Zhang (2012) observed a multimodal age distribution with peaks during 1840-1860 and in recent years. The differential spatio-temporal regeneration pattern reflected in the unimodal to multimodal size (age, DBH and/or height) class distributions were also observed in various treelines sites of different mountains: for example *Picea schrenkiana* in central Tianshan Mountains NW China (Wang et al., 2006), *Juniperus przewalskii* in the Qilian mountains, NE Tibetan Plateau (Gou et al., 2012), *Pinus uncinata* in the Pyrenees Mountains, NE Spain (Camarero & Gutiérrez, 2007; Batllori & Gutiérrez, 2008), *Picea glauca* in SW Yukon, Canada (Danby & Hik, 2007), *Larix gmelinii* in the Putorana Mountains, northern Siberia (Kirdyanov et al., 2012), *Picea glauca*, *Picea mariana* and *Larix laricina*, *Abies lasiocarpa* near Churchill, Manitoba, Canada (Mamet & Kershaw, 2012).

4.3 Climate, tree growth and growth-climatic response

4.3.1 Climatic trend in study area

4.3.1.1 Climatic trend in Sagarmatha National Park region

The climate in the SNP region is semi-arid with significant differences between the humid southern valleys, under major influence of the Indian summer monsoon, and the arid northern ones affected by the desiccation effects of the Himalaya range. About 80% of the annual precipitation occurs in the monsoon season (June to September) with heavy snow accumulation during winter; while rest of the year is dry (Fig. 25). Precipitation is low as the park is in the rain shadow of the Karyalung-Kangtega range. Annual precipitation is about 984 mm in Namche Bazar (3,440 m, asl) and it decreases with the elevation and comes around 516 mm per year at Pyramid lab (5050 m, asl) (Fig. 25 and Thakuri et al., 2014). Despite the fairly short and scarce meteorological records within the area both a local-based analyses (Salerno et al., 2015) and the global CRU dataset (Harris et al., 2014) converge in describing a significant increase in temperature, mostly concentrated outside of the monsoon period together with a precipitation weakening during the monsoon season. The CRU grid based temperature analysis revealed an increase in the average annual maximum, minimum and mean temperature, though less pronounced compared to station data (Fig. 25b). The precipitation in the Chaurikharka station in Solukhumbu district is also increasing (Fig 25c) while grid based precipitation (CRU TS3.22) did not significantly change but shows a slightly decreasing trend (Fig. 25c).

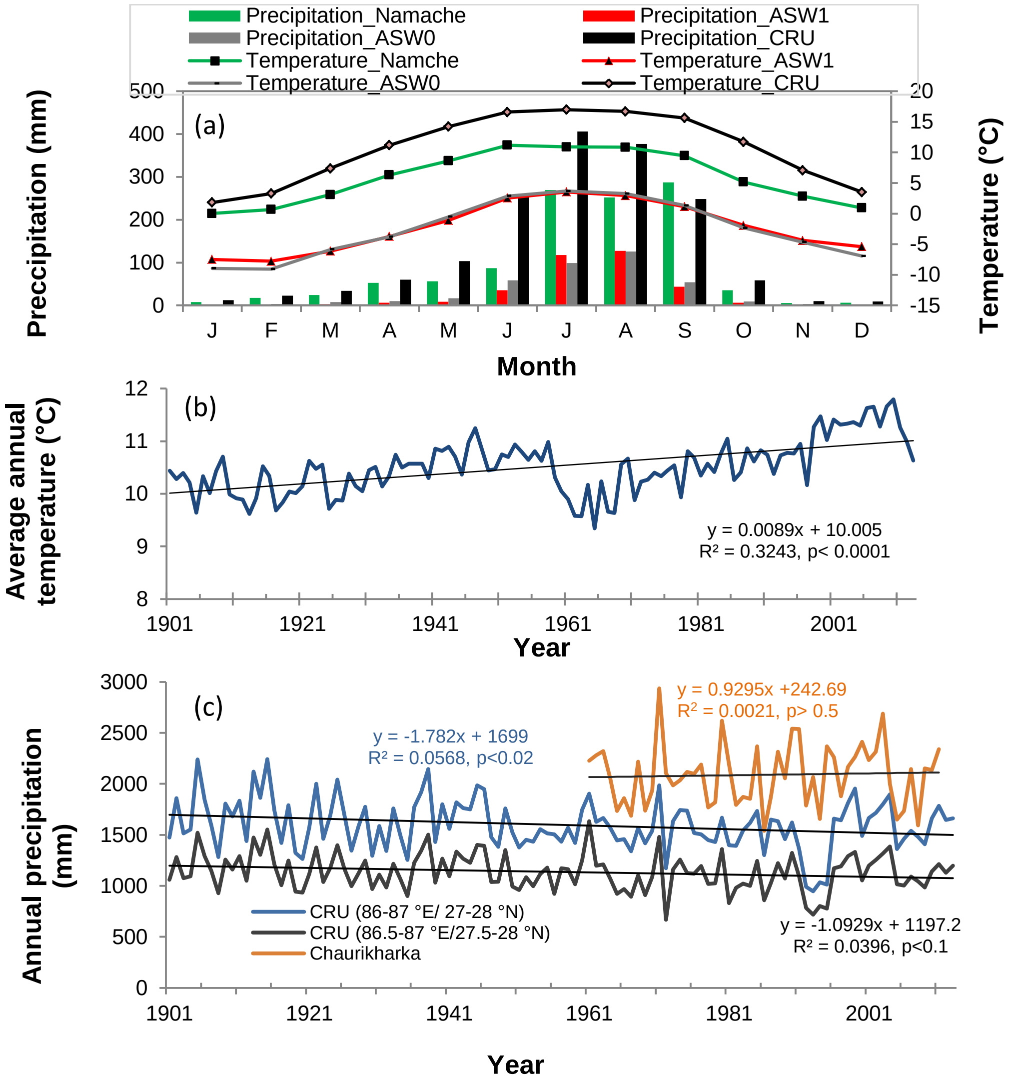


Figure 25: Climograph of the Sagarmatha National Park area (a); Annual trend of grid based CRU mean temperature (b); and annual trend of grid based CRU and Chaurikharka precipitation (c). J to D are name of months starting from January to December

4.3.1.2 Climatic trend in Manaslu Conservation Area region

The climate of the MCA region is also monsoon dominated (Fig.26). The mean annual rainfall over the past 30 years (1980-2009) at nearby meteorological station at Chame was 967 mm (SD = 280). The monthly average temperature was found to be highest in July and lowest in November (Fig. 26a). The highest recorded temperatures were 23.4 °C during June 1998, the lowest -4.5 °C during January of 1999 and 2000.

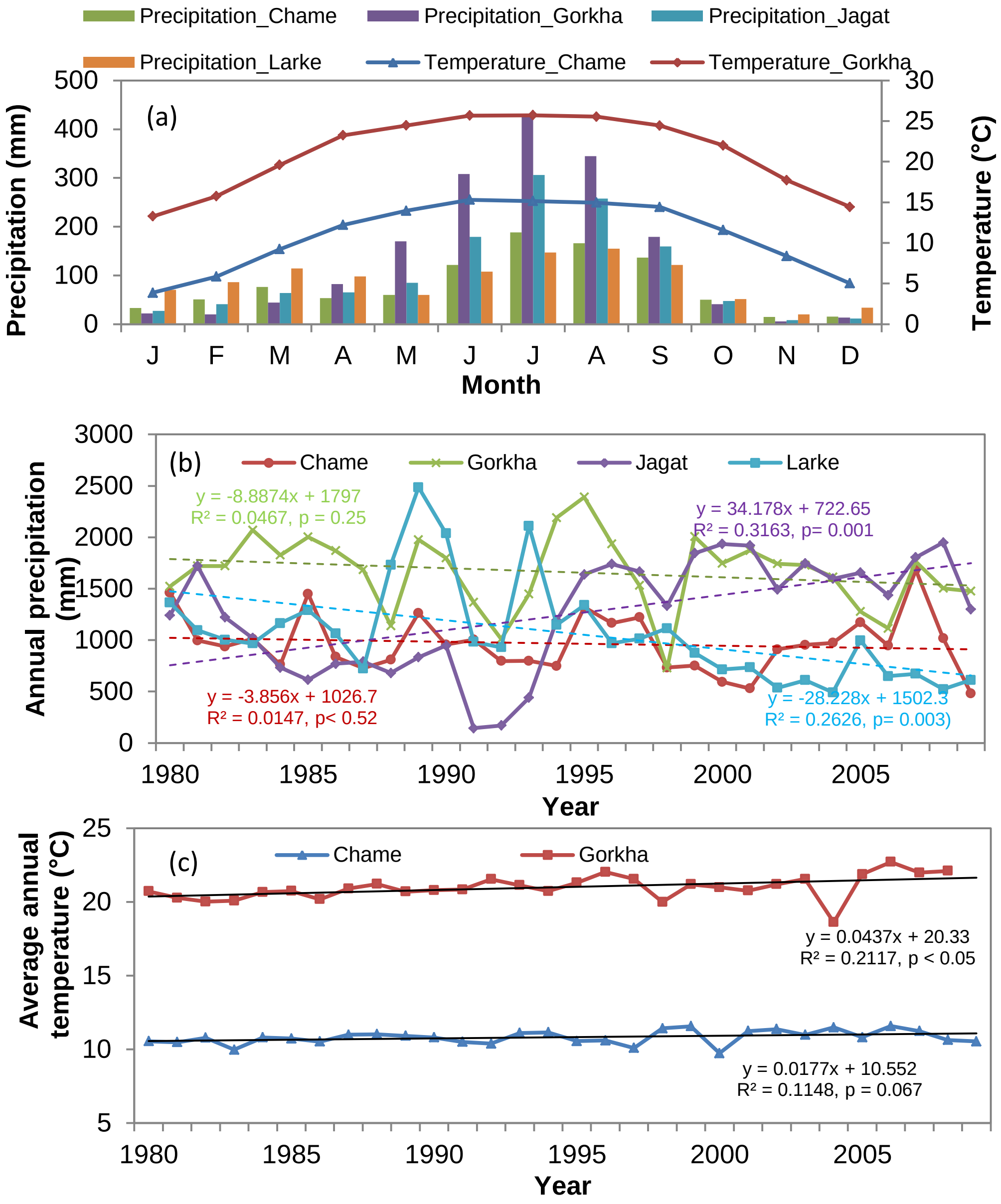


Figure 26: Climograph of Manaslu Conservation Area (a); annual trend of precipitation in the local meteorological station (b) and annual temperature trend in Chame and Gorkha station. J to D are name of months starting from January to December

During the past 30 years (1980-2009), the Chame station experienced a decreasing trend in rainfall by 3.9 mm/yr (n = 30, R^2 = 0.014, $p < 0.52$) (Fig. 26b) and an increasing trend in mean annual temperature by 0.017 °C/yr (Fig. 26c). In this station monthly mean minimum temperature was decreasing while monthly mean maximum temperature was increasing significantly (Fig. 26d). Similarly, mean annual rainfall at Jagat and Larke, Gorkha was 1252 mm (SD = 535) and 1065 mm (SD = 485) respectively. In Larke, during the past 30 yrs (1980-2009) there was a significant (n = 30, R^2 = 0.26, $p < 0.003$) decreasing trend of rainfall by 28 mm/yr (Fig. 26b). 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 between 1987 and 2009.

4.3.1.3 Climatic trend in Rara National Park region

Climate of the Rara National Park (RNP) region is influenced by both Indian summer monsoon, and winter monsoon also known as western disturbances. Figure 27 shows the monthly temperature and precipitation in and around RNP region. The monthly average temperature was found to be highest in July and lowest in January (Fig. 27). The climate of the study area is monsoon dominated with contribution of monsoon precipitation to annual total in local stations ranged from 55% to 74%. However, compared to eastern Nepal contribution of summer monsoon in annual precipitation is less. The mean annual rainfall in local meteorological station namely Jumla, Guthichaur and Mugu was 794 mm (SD = 140), 1076 mm (SD = 215), 726 mm (SD = 347), respectively.

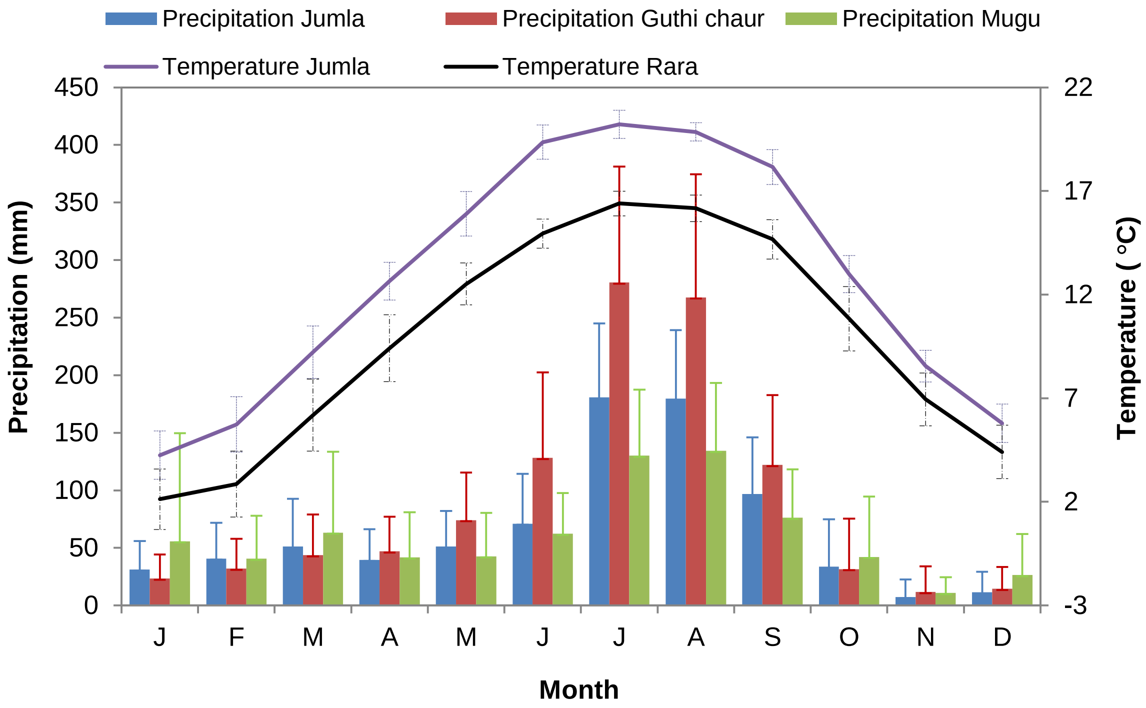


Figure 27: Climograph of the Rara National Park, Nepal Himalaya. The error bar indicates standard deviation from the mean value. J to D are name of months starting from January to December

The annual precipitation in the Jumla and Guthichaur, Jumla stations is slightly increasing while in Mugu station is significantly decreasing (Table 8 & Fig. 28b).

Seasonal trends are site specific (Fig. 28, Table 8). In Mugu stations the precipitation is significantly decreasing in all seasons while in other two stations there is no significant change in the seasonal precipitation with slight increase in the premonsoon and monsoon season in Jumla (Table 8). In Jumla station, mean annual temperature is significantly increasing by 0.021 ^{o}C/yr ($n = 44$, $r = 0.54$, $p < 0.01$) (Fig. 28a) during 1969-2012 AD while annual total rainfall is increasing by 1.76 mm/yr during 1957-2012 AD, but not significant statistically ($n = 56$, $r = 0.2$, $p > 0.05$) (Fig. 28b). In Jumla, temperature during all seasons is increasing significantly with higher rates in summer and autumn (Table 8 & Fig. 28c). In Guthichaur, there was no significant change in annual precipitation during past 37 year (1976-2012 AD) (Table 8 & Fig. 28b). In Rara station, from 1988 to 2006 AD, annual temperature was increased by 0.025 ^{o}C/yr with significant increase in winter temperature ($r = 0.47$, $P < 0.05$) (Table 8; Fig. 28a & f).

Table 8: Monthly and seasonal and annual climate trend in Rara National Park (Correlation coefficient). Values in bold figures represent the trend significant at 95% confidence or higher limit. Jan to Dec are the name of the months starting from January. DJF = December to February, MAM = March to May; JJAS = June to September, ON = October Npvember

	Stations				
Month & Season	Jumla precipitation	Jumla temperature	Guthichaur precipitation	Mugu precipitation	Rara temperature
Jan	-0.16	0.26	-0.01	**-0.33**	0.18
Feb	0.06	**0.31**	0.22	-0.18	0.32
Mar	-0.02	**0.33**	-0.2	**-0.33**	0.24
Apr	0.19	0.24	-0.03	**-0.45**	0.11
May	0.25	0.17	-0.13	**-0.31**	0.08
Jun	0.14	**0.34**	-0.08	-0.12	0
Jul	-0.06	**0.39**	0.02	**-0.52**	-0.01
Aug	0.15	**0.58**	0.1	**-0.54**	0.08
Sep	0.14	**0.49**	0.01	**-0.34**	0.05
Oct	-0.03	**0.29**	0.1	-0.2	-0.09
Nov	0.17	**0.38**	0.12	0.27	-0.15
Dec	-0.03	0.21	-0.17	-0.18	**0.58**
DJF	-0.08	**0.34**	0.07	**-0.38**	**0.47**
MAM	0.17	**0.34**	-0.18	**-0.43**	0.23
JJAS	0.16	**0.57**	0.04	**-0.52**	0.04
ON	0.03	**0.4**	0.14	-0.12	-0.12
Annual	0.2	**0.54**	0.02	**-0.53**	0.3

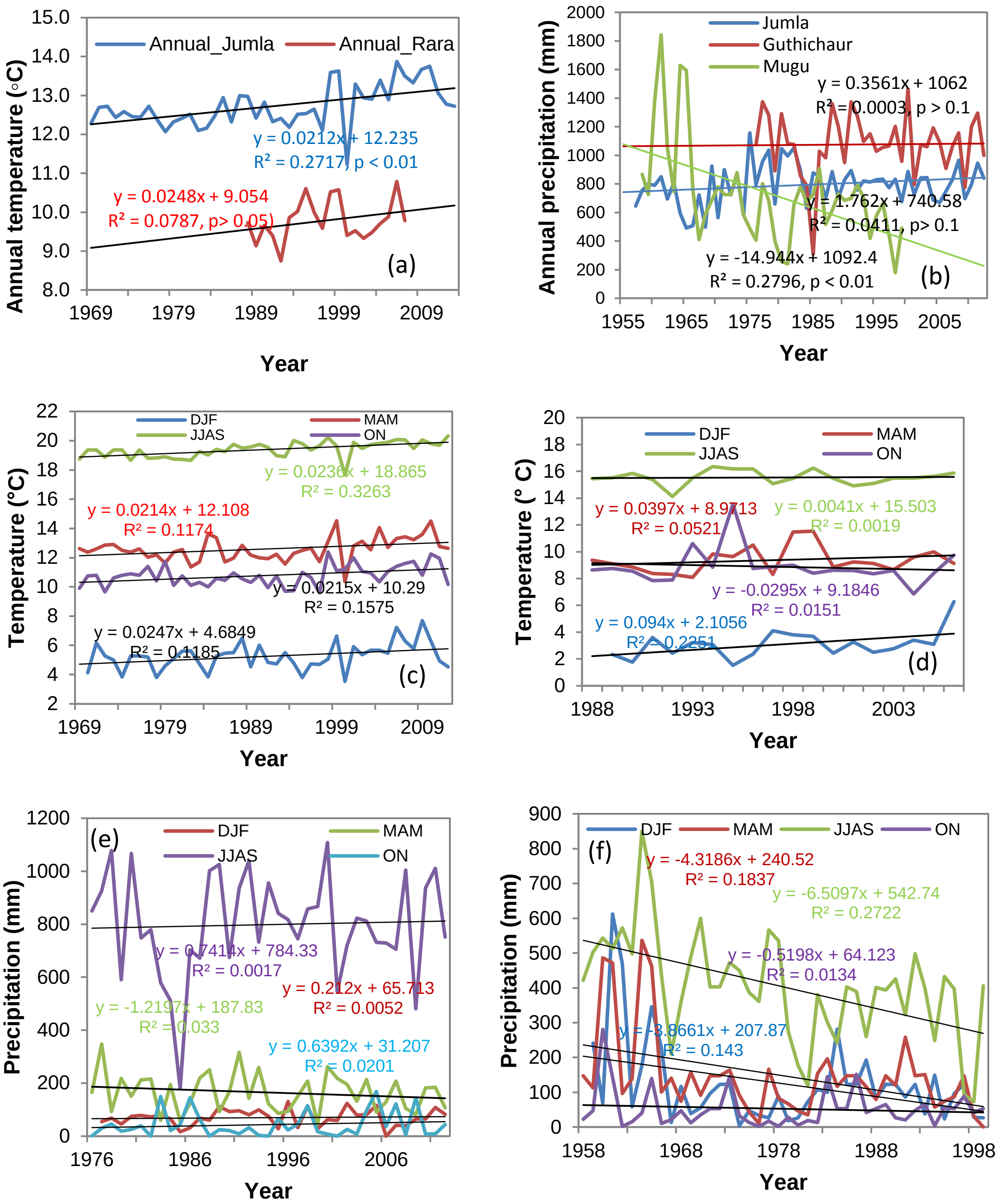


Figure 28: Seasonal and annual trend of temperature and precipitation in the meteorological station in and around Rara National Park, Nepal Himalaya.

The climatic trend observed in present study is consistent with the national or regional trend with an increase in average annual temperature and not consistent (increasing or decreasing) trend in the precipitation (Shrestha et al., 1999, 2000; Shrestha & Aryal, 2011; Shrestha et al., 2012, Kattel & Yao, 2013; Qi et al 2013; Salerno et al., 2015).

4.3.2 Ring-width chronology from Sagarmatha National Park

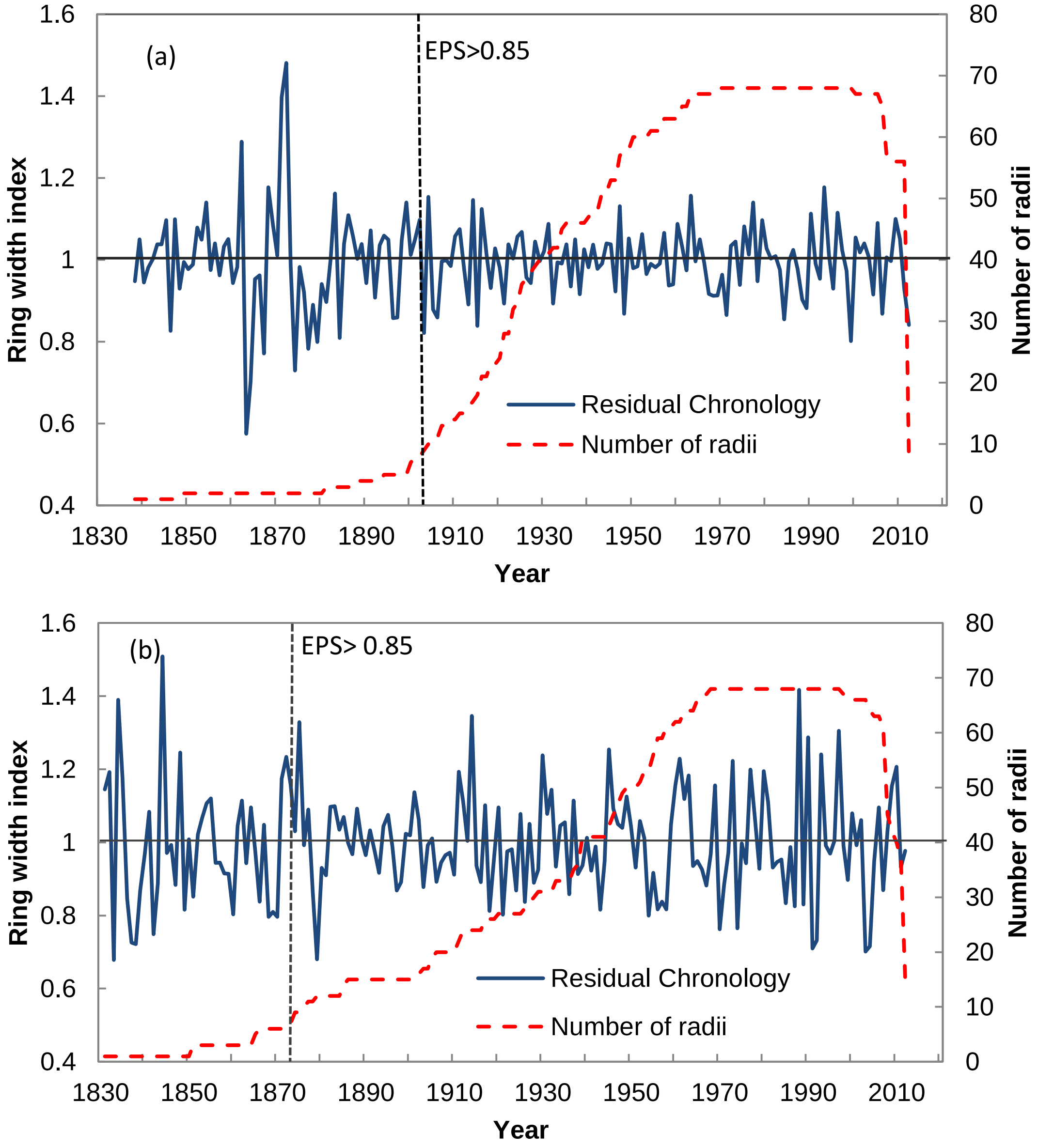


Figure 29: Tree ring-width residual site chronologies of *Abies spectabilis* (a) and *Betula utilis* (b) from the treelines of the Sagarmatha National Park, Nepal Himalaya.

Based on the ring-width analysis, two ring-width site chronologies of *Abies spectabilis* and *Betula utilis* were prepared (Fig. 29). The site chronology of *A. spectabilis* extended to 1838-2012 AD, while that for *B. utilis* ranged 1831-2012 AD. The chronology characteristics (Table 9) show the dendroclimatic potential of these chronologies (Fritts, 1976; Cook & Kairiukstis, 1990; Speer, 2010). The chronologies of *A. spectabilis* and *B. utilis* did not show persistent pattern of growth enhancement in the chronology rather it fluctuates over time.

Table 9: Chronology characteristics of the residual ring-width chronologies of *A. spectabilis* and *B. utilis* in the Sagarmatha National Park, Nepal Himalaya

Parameters	*Abies spectabilis*	*Betula utilis*
Number of cores (trees)	68 (50)	68 (48)
Period of record	1838-2012	1831-2012
Mean sensitivity (raw)	0.143	0.29
Mean series length (year)/max	85 (174)	86 (178)
Mean index (SD) (mm)	0.995 (0.12)	0.996 (0.15)
Common period	1932-2007	1940-2007
Number of cores (trees)	42 (34)	35 (22)
Mean sensitivity	0.11	0.15
First-order autocorrelation	0.16	0.05
Mean inter-series correlation	0.29	0.40
Within tree	0.59	0.65
Between tree	0.29	0.40
Express population signal	0.94	0.96
Signal to noise ratio	17.29	23.53
Variance explained (%)	31.7	43
EPS>85% (no of sample)	14	9
Year crossing EPS >0.85	1909	1874

4.3.3 Growth-climate response in Sagarmatha National Park

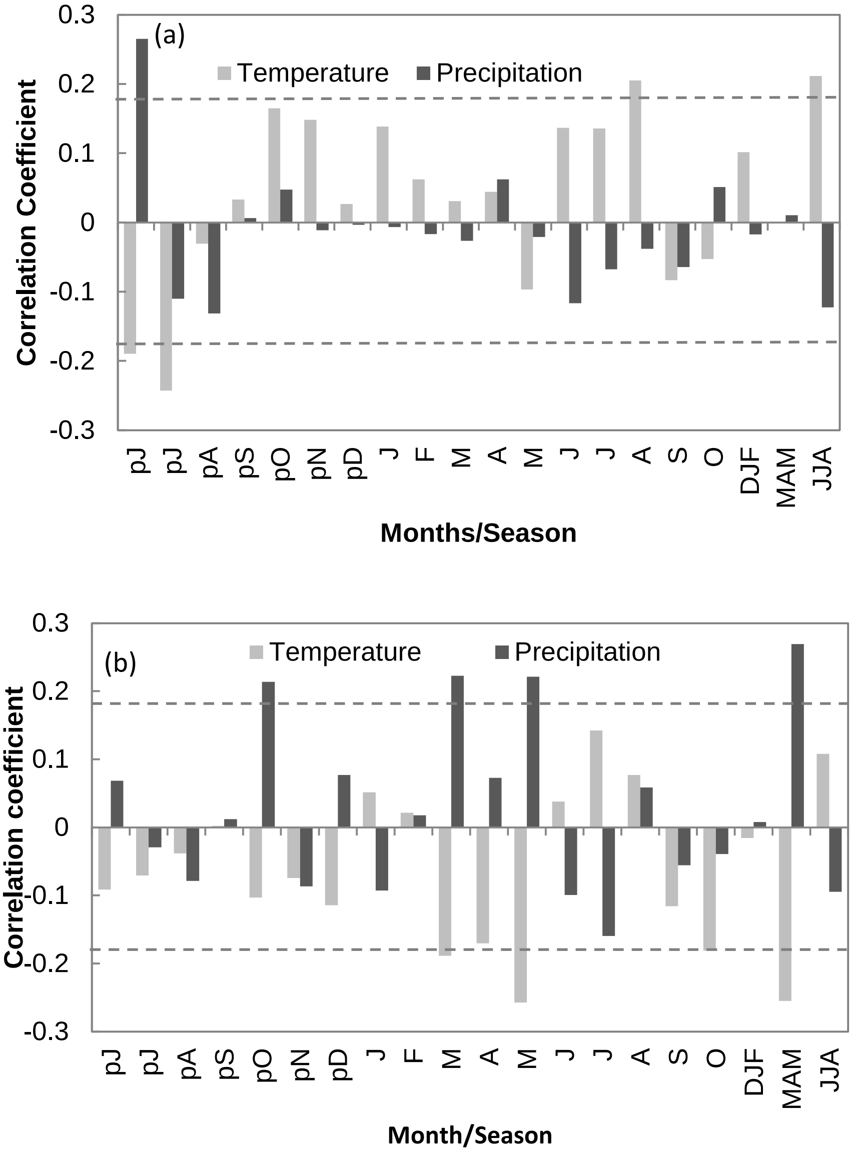


Figure 30: Correlation (Pearson's correlation) between the radial growth (Ring width residual chronology) of *Abies spectabilis* (a) and *Betula utilis* (b) with monthly climate data in the study area of Sagarmatha National Park, Nepal Himalaya. The horizontal dash line indicates correlation coefficient significant at 95% or more confidence level. The pJ to pD indicates months of previous year July to December and J to O indicates months of current year starting from January; DJF, MAM and JJA represents the seasonal average climate of winter (December to February), spring (March to May) and summer (June to August), respectively.

Figure 30 reveals simple correlation coefficient between the radial growth of *Abies spectabilis* and *Betula utilis* and climatic parameters. Consistent to the global and regional pattern, the radial growth of *A. spectabilis* growing in the treelines of the SNP is mainly limited due to the low temperatures during summer (JJA) growing season. There was a significant positive relationship with average monthly temperature of August ($p < 0.05$) and average temperature of summer season (JJA) (Fig. 30a). As summer season is monsoon season providing water supply for the growth, high temperature during this month's lead to high growth and formation of wider rings. The temperature of the autumn of the pre growing year also has a positive relationship with the radial growth. The high precipitation during the June of previous growing year also positively favors the growth of *A. spectabilis*.

The correlation function analysis revealed that there was a significant positive relationship ($p < 0.05$) between the radial growth of the *B. utilis* and monthly precipitation of October previous year, March and May months of the current year, spring season (MAM) precipitation, while a significant negative relationship with temperature of same season (Fig. 30b). There was a positive relationship between the radial growth and summer season temperature, though not significant statistically. This indicates that radial growth of the *B. utilis* at treeline of SNP was mainly limited by the moisture stress during spring season as well as low temperature during growing summer season.

4.3.4 Ring-width chronology from Manaslu Conservation Area

For MCA, a 229 year long (1782-2010 AD) standard tree ring chronology of *A. spectabilis* was prepared using 46 cores from 29 trees (Fig. 31a). 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. Results (cf Gaire et al., 2014 for details) of the regime shift analysis (Rodionov, 2004, 2006) suggest that there have been constant changes in mean radial growth which are dominated by short periods of above-average radial growth. Two major periods with low radial growth were 36 years starting in 1854, and 63 years starting in 1940s. The period centered on 1905 is one of the shortest with below-average radial growth. In the recent period (after 2000) the radial growth is increased.

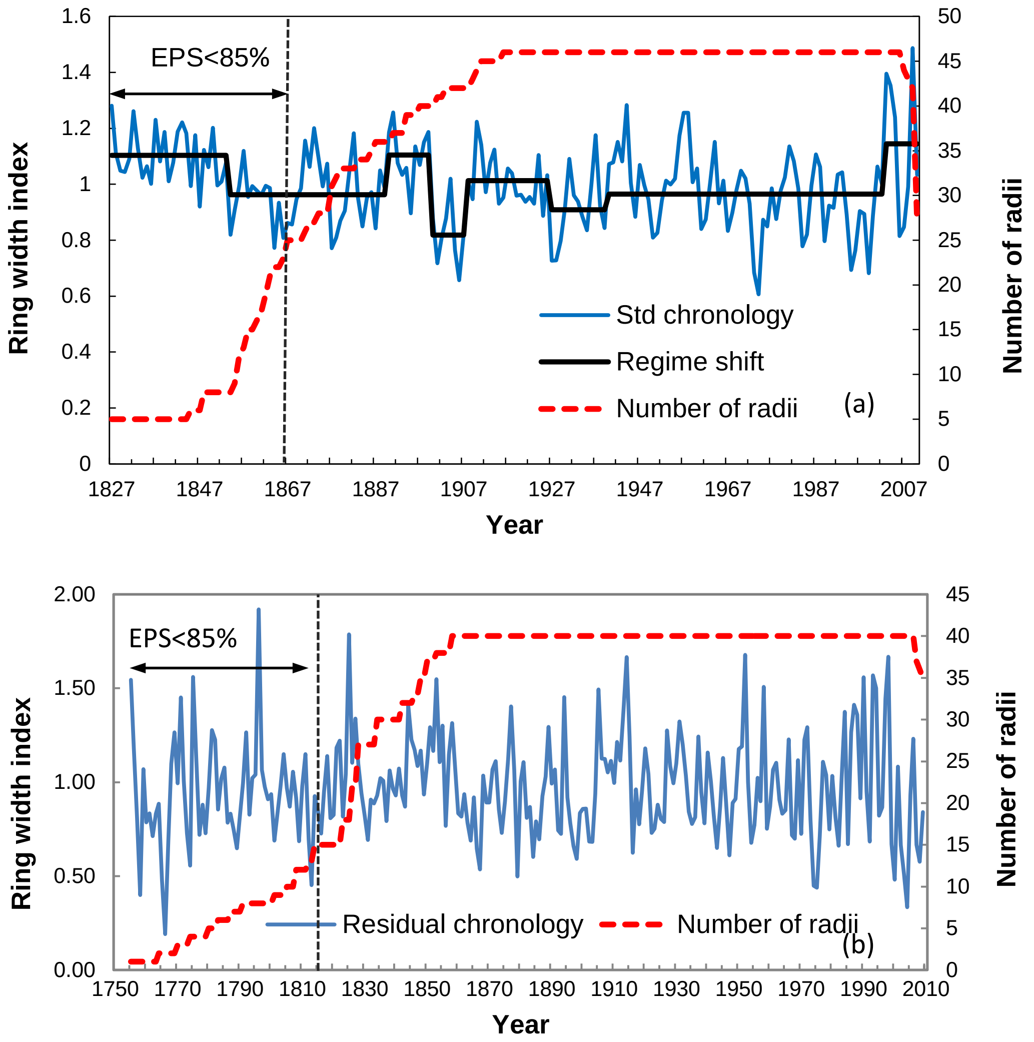


Figure 31: Tree ring standard chronology of *Abies spectabilis* (a) and *Betula utilis* (b) from the Kalchuman lake area of Manaslu Conservation Area, Nepal Himalaya

Several statistics (Table 10) 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 (Fritts, 1976; Cook & Kairiukstis, 1990; Speer, 2010). 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%. The *B. utilis* chronology (Fig. 31b) also has good dendrochronological potential as it was prepared by crossdating with and taking reference of previously reported master chronology from the same site (Liang et al., 2014).

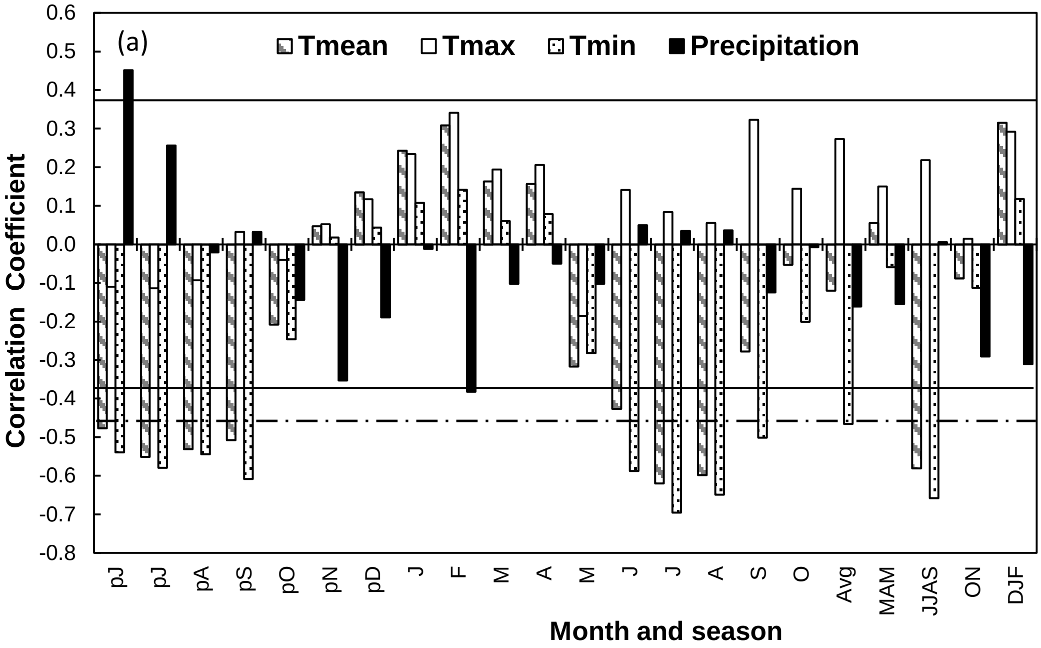
Table 10: Selected statistics of tree-ring chronology of *Abies spectabilis* from Kalchuman Lake area, Manaslu Conservation Area, Nepal Himalaya

Statistics	**Standard Chronology**
Chronology Time Span	A.D. 1782-2010
Number of Trees (radii)	29 (46)
Mean Sensitivity	0.136
Standard Deviation	0.18
AR modeling order 1	0.592
Common Interval Time Span	A.D. 1920-2005
Number of Trees (radii)	24 (39)
Mean correlation among all radii	0.196
Mean correlation between trees	0.192
Mean correlation within trees	0.467
Signal-to-noise ratio	11.23
Expressed population signal	0.918
Variance explained by first eigenvector	24.4%

4.3.5 Growth-climate response in Manaslu Conservation Area

The radial growth of the *Abies spectabilis* at the treeline of Kalchuman lake area was limited by the low temperature with a positive correlation between the ring width chronology and monthly maximum temperature in most months and a negative relationship with minimum temperature (Fig. 32a). The radial growth in *A. spectabilis* correlated negatively with the mean and minimum monthly temperature of June–September ($r > -0.45$, $p < 0.01$) months of the current year (Fig. 32a). However, above-average monthly mean and minimum temperature in the previous year growing period (i.e. June–September) influence negatively the current year growth. Looking at the influence of seasonal climate on the growth, effect of monsoon season (JJAS) temperature on the growth was stronger than individual counterpart months with a significant negative correlation with seasonal mean ($r = -0.58$, $p < 0.01$) and minimum ($r = -0.66$, $p < 0.01$) temperature. Though weak, radial growth was negatively correlated with monthly precipitation of most months of the current year (Fig. 32a). The relationship between ring width and precipitation of February of the current year was slightly negative ($r = -0.38$, $p < 0.05$). The precipitation during the previous year June correlated positively ($r = 0.45$, $p < 0.05$) with current year growth.

The correlation between the radial growth and seasonal sum of precipitation was weak and not significant statistically.



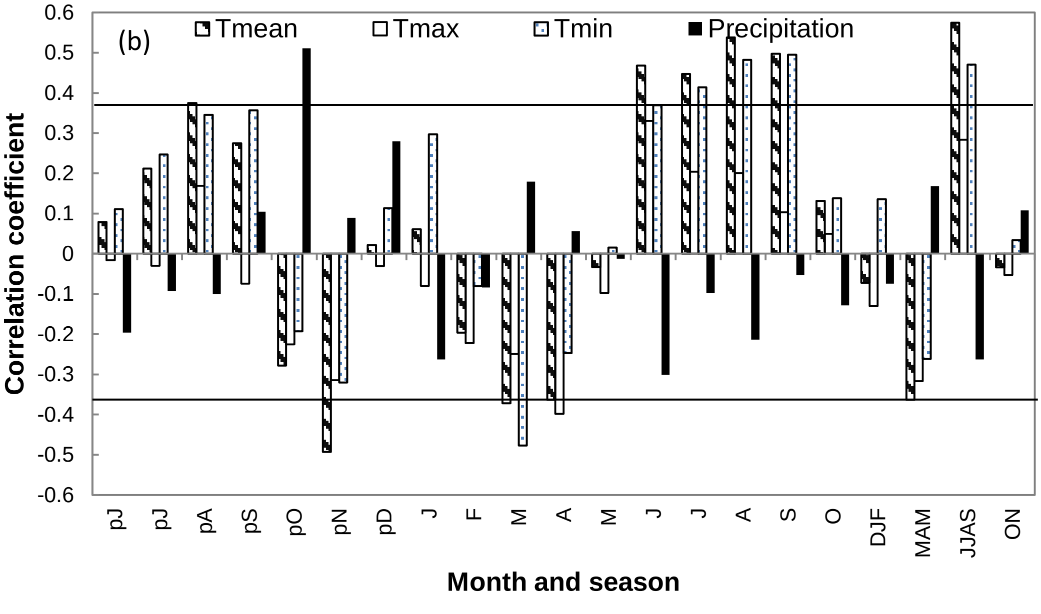


Figure 32: Relationship between the *Abies spectabilis'* (a) and *B. utilis* (b) radial growth with climate data (monthly mean, maximum, minimum, seasonal average temperature, and monthly and seasonal sum of precipitation) in Manaslu Conservation Area, Nepal Himalaya; The black horizontal line indicates a significant correlation at the 95% confidence limit for a two-tailed test and dashed horizontal line indicates a significant correlation at the 99% confidence limit for a two-tailed test. Figure shows the response of radial growth to the monthly climate of June in the previous year to October of the current year as well as seasonal averages. pJ-pD signify June-December of the previous year; MAM, JJAS, ON and DJF are the mean temperature and the sum of precipitation from March to

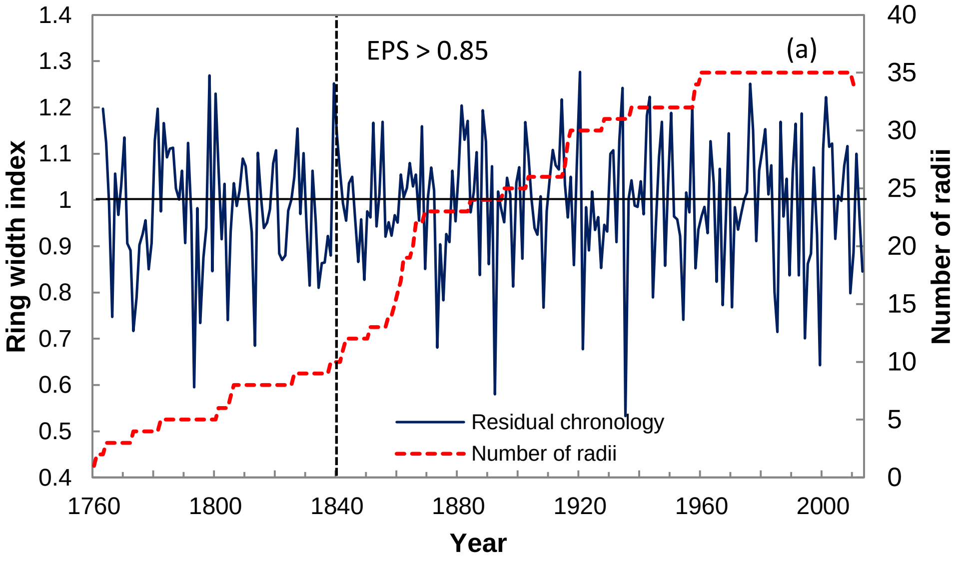
May, June to September, October-November, and previous year December to the current year February, respectively.

The radial growth of the *Betula utilis* at the treeline of Kalchuman lake area was limited by the temperature induced moisture stress during spring season and low or insufficient temperature during the summer months resulted from the high cloud covergare during the monsoon season (Fig. 32b). The radial growth of *B. utilis* correlated negatively with the mean monthly temperature of previous year November, current year March, April and spring (MAM) season ($r > -0.36$, $p < 0.05$) (Fig. 32b). However, above-average monthly mean and minimum temperature during the summer growing period (June to September) favored positively for the radial growth ($r > 0.37$, $p < 0.05$). Looking at the influence of seasonal climate on the growth, effect of monsoon season (JJAS) temperature on the growth was stronger than individual counterpart months with a significant positive correlation with seasonal mean ($r = 0.57$, $p < 0.05$) and minimum ($r = 0.47$, $p < 0.05$) temperature (Fig. 32b).

Radial growth of *B. utilis* was negatively correlated with monthly precipitation of most months of the current year (Fig. 32b). The relationship between ring width and precipitation of spring months of the current year was slightly positive while precipitation during the previous year October was correlated significantly positively ($r = 0.51$, $p < 0.05$) with current year growth. The correlation between the radial growth and seasonal sum of precipitation was weak and not significant statistically.

4.3.6 Ring-width chronology from Rara National Park

Based on the ring-width analysis of the samples (Table 11), two ring-width site chronologies, each of *Abies spectabilis* and *Betula utilis*, were prepared from the RNP (Fig. 33). The site chronology of *Abies spectabilis* extended to 1763-2013 AD (Fig. 33a), while that for *Betula utilis* ranges 1872-2013 AD (Fig. 33b). The chronology characteristics (Table 11) show the dendroclimatic potential of these chronologies (Fritts, 1976; Cook & Kairiukstis, 1990; Speer, 2010). In the *A. spectabilis* chronology, the years 1731, 1873, 1892, 1921, 1935, 1985, and 1999 have low growth, while years 1798, 1839, 1888, 1920, and 1976 have high growth. In *B. utilis* chronology, years 1893, 1927, 1972, and 2007 have high growth while years 1885, 1936, 1955, 1985, and 1999 have lowest growth. The chronologies of *A. spectabilis* and *B. utilis* did not show persistent patterns of growth enhancement in the recent years.



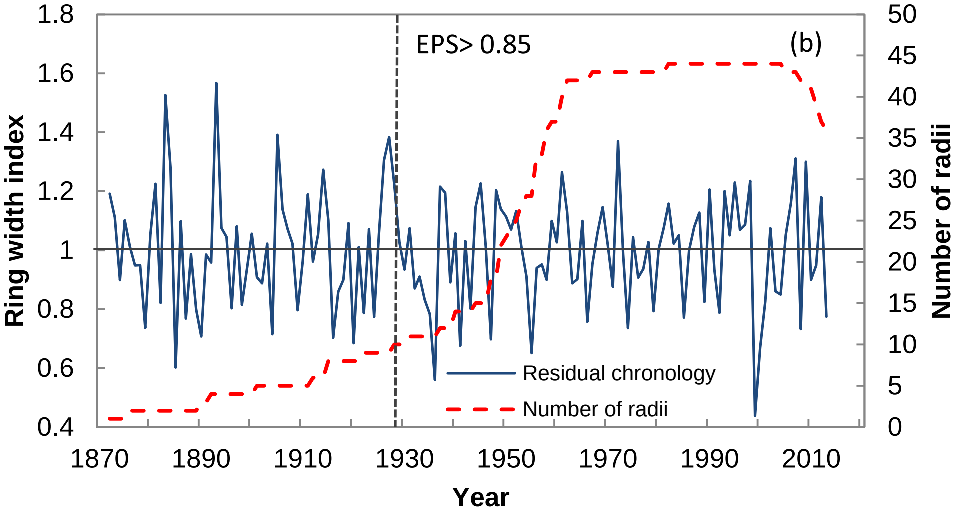


Figure 33: Tree ring-width residual site chronologies of *Abies spectabilis* (a) and *Betula utilis* (b) from the treelines of the Rara National Park, Nepal Himalaya.

Several statistics that were calculated for the whole chronology time span and for the period of overlap of all tree-ring series indicated a high dendrochronological potential (Table 11). The average growth of *Abies spectabilis* was (1.361 ± 0.63 mm SD) lower than that of *Betula utilis* (1.409 ± 0.77 mm SD). The value of mean sensitivity of *A. spectabilis* was lower than that of *B. utilis*. The EPS, an indication of how well the site chronology estimates the population chronology, was above the threshold limit of

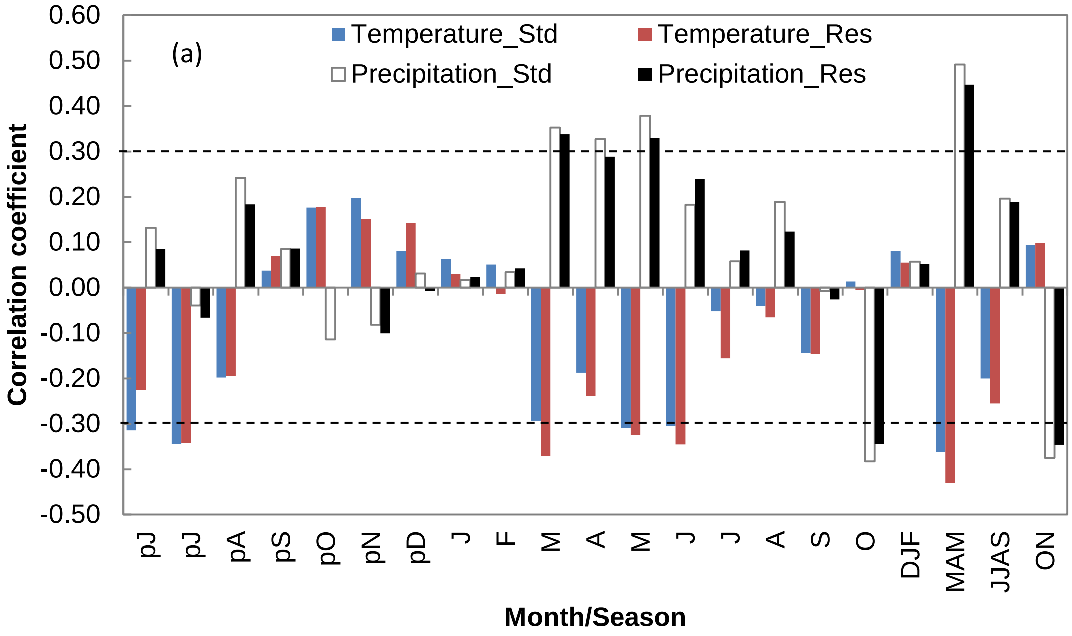
0.85 (Wigley et al., 1984) in both species i.e. *A. spectabilis* (0.938) and *B. utilis* (0.947). The signal to noise ratio and the percentage of variance explained by the first eigenvector were high in *B. utilis* than *A. spectabilis*. All parameters show that *B. utilis* is more sensitive than *A. spectabilis* which might be due to more sample depth in *B. utilis*.

Table 11: Selected statistics of tree-ring width chronology of *Abies spectabilis* and *Betula utilis* from the treelines of the Rara National Park, Nepal Himalaya

	Abies spectabilis		*Betula utilis*	
Parameters	Standard	Residual	Standard	Residual
Growth (raw index)/ SD	1.361/0.628	1.361/0.628	1.409/0.773	1.409/0.773
Chronology length	1763-2013	1763-2013	1872-2013	1872-2013
No of cores	35	35	44 (36)	44 (36)
Common period	1940-2013	1940-2013	1960-2013	1960-2013
Mean sensitivity	0.136	0.152	0.231	0.231
AR modeling		2		2
First-order autocorrelation	0.285	-0.047	0.209	-0.014
Mean inter-series correlation	0.303	0.327	0.376	0.383
Within tree	0.584	0.585	0.698	0.714
Between tree	0.298	0.322	0.374	0.381
Express population signal	0.931	0.938	0.946	0.947
SNR	13.446	15.039	17.443	17.996
Variance in first principal component (%)/VF	33.4	35.7	40.05	41.2
EPS > 0.85	14	12	10	10

4.3.7 Growth-climate response in Rara National Park

The growth climate response revealed that the growth *A. spectabilis* of the RNP area is mainly limited due to moisture stress during pre-monsoon/spring months and seasons (Fig. 34a). There was a significant ($p < 0.05$) positive relationship between the growth and precipitation in March, April and May months and spring season (MAM). A year with high precipitation positively favours the growth with significant positive relation ($p < 0.05$) with annual precipitation. A high temperature during spring and summer negatively affected the growth with a significant ($p < 0.05$) negative relationship with average monthly temperature of March, May and June and seasonal average of spring and summer season. The relationship is different along the elevation gradient. In the treeline ecotone, growth climate relationships are generally weak; however a high temperature during summer with sufficient moisture positively favors tree growth.



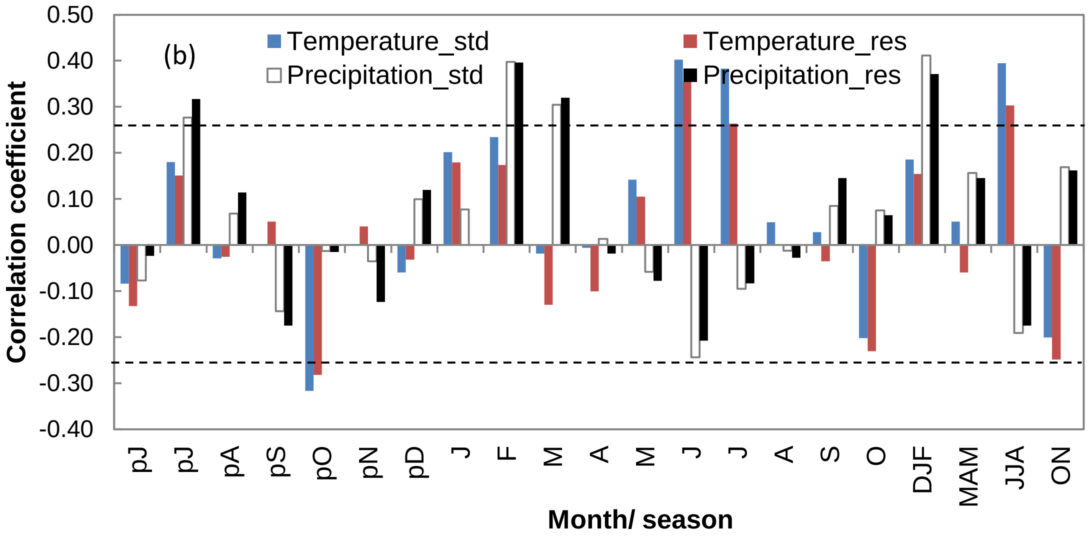


Figure 34: Relationship between the *Abies spectabilis'* (a) and *B. utilis* (b) radial growth with climate data (monthly mean and seasonal average temperature, and monthly and seasonal sum of precipitation) in Rara National Park, Nepal Himalaya; The dashed black horizontal line indicates a significant correlation at the 95% or above confidence limit for a two-tailed test. Figure shows the response of radial growth to the monthly climate of June in the previous year to October of the current year as well as seasonal averages. pJ-pD signify June-December of the previous year; MAM, JJAS, ON and DJF are the mean temperature and the sum of precipitation from March to May, June to September, October-November, and previous year December to the current year February, respectively.

The growth climate response revealed that the growth of *Betula utilis* from the treeline of RNP area is mainly limited due to low precipitation during pre-monsoon months and insufficient temperature during summer (Fig. 34b). There was a significant ($p < 0.05$) positive relationship between the growth and precipitation in previous year July, current year February, March, and winter season (DJF). A high temperature during summer months and seasons positively affected the growth with a significant ($p < 0.05$) positive relationship with average monthly temperature of June and July of the current year and average temperature during summer season (JJA).

Growth of a tree is associated with several biotic and abiotic factors including climate (Fritts, 1976; Speer, 2010). The radial growth of *Abies spectabilis* and *Betula utilis* fluctuated over time with changing climate and we did not observe constant increment or decrement in the growth. A few studies on *Pinus wallichiana*, *Cedrus deodara*, and *Picea smithiana* from high-altitude forests and treelines in Kinnaur and Gangotri region, India have showed an unprecedented growth enhancement during recent decades (Singh & Yadav, 2000; Borgaonkar et al., 2009, 2011). Similar enhancement in the growth was also observed in the conifer species from Tibet and adjacent mountain regions (Gou et al., 2007; Liang et al., 2009, 2010). Recent enhancement in growth of trees with climate change is not a common observation in the HKKH and adjacent regions (Cook et al 2003, 2010; Bhattacharyya & Shah 2009; Ahmed, 2014; Shah et al., 2014).

Depending upon the site and precipitation regime, the growth of *Abies spectabilis* and *Betula utilis* in the treeline is limited by temperature and or precipitation. As *A. spectabilis* is evergreen conifer and *B. utilis* is deciduous broadleaved species, their sensitivity and response towards climate is slightly different in month–to–month comparison. The radial growth of *A. spectabilis* in the treeline is more sensitive and responsive to temperature change than precipitation. Consistent to other many studies, tree growth–climate relationships of *A. spectabilis* near treeline in western Nepal was negative with spring season (MAM) temperature and positive with same month's precipitation. The growth of the *A. spectabilis* in the MCA is favored by the warm winter temperature and cool summer. Tree growth of *A. spectabilis* in MCA was positively correlated with temperature from October of the previous year to April of the current year which indicates that temperature before the growing season has a main influence on the radial growth during subsequent growing period. Studies also have reported that monthly and seasonal winter temperatures are more limiting than growing season temperatures to annual radial growth in many upper treeline sites with a positive relationship with winter temperature (Bräuning, 2004; Pederson et al., 2004; Borgaonkar et al., 2011). Warmer conditions during winter and autumn season facilitate the storage of higher levels of hydro-carbonates and are beneficial to root system activity, carbon absorption and transportation (Pederson et al., 2004; Fan et al., 2009; He et al., 2013). As treeline sites of Himalayas receive winter precipitation in the form of snow, warm winters also contribute to early melting of snow and supplying water for growth initiation during the growing period.

Bräuning (2004) found a strong positive relationship between the *A. spectabilis* ring width chronology and temperature from November of the previous year to January of the current year in the western Nepal. Borgaonkar et al. (2011) found a strong positive relationship between the mean annual and winter (DJF) temperatures of the concurrent year and growth of western Himalayan conifers. The negative relationship, observed in the MCA region in present study, with the pre-monsoon (MAM) and monsoon season (JJAS) temperature indicated towards some threshold temperature or moisture stress because increase in temperature in the pre-monsoon and monsoon season without adequate rainfall increases the evapotranspiration which leads to a soil-moisture deficit and limits tree growth (Fritts, 1976; Cook et al., 2003; Yadav et al., 2004). The response observed between the growth and temperature during summer months and seasons in MCA, is also observed in the growth climate relationship of the many conifers from the dry sites of the Nepal Himalaya (Cook et al., 2003; Kharal et al., 2014) and in western Indian Himalaya (Yadav, 2011; Yadav et al., 2011). Climate system in western part of Nepal is slightly different from eastern part which is reflected in the response of tree growth to climatic conditions. The radial growth of the *A. spectabilis* growing in the treelines of the SNP is mainly limited due to the low temperatures during summer (JJA) growing season with a significant positive relationship with average monthly temperature of August and average temperature of summer season (JJA). As summer season is the monsoon season providing sufficient water supply for growth, high temperature during these months and season lead to high growth at the treelines of SNP area. This response in SNP is almost similar to the climate-growth response of the conifers from the eastern

Himalaya (Chaudhary & Bhattacharyya, 2000; Bhattacharyya & Chaudhary, 2003) but different details exist in month to month comparisons. The radial growth of the *A. spectabilis* at the timberline of the Tibetan side of the Everest region was positively related with both temperature and PDSI throughout the year, showing a significant positive relationship with temperature during winter and summer months (Lv & Zhang, 2012). Other studies mainly from central and western part of 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 & Thapa., 2010; Gaire et al., 2011; Kharal et al., 2014). Most of these studies were carried out in the areas lower than treeline ecotone. Similarly, Yadav et al. (2004a) obtained a negative as well as weaken relationship between the mean temperature of the summer months and growth of *A. spectabilis* from treeline sites of the western Himalaya of India. In the present study, responses of radial growth of *A. spectabilis* from MCA to minimum and maximum temperatures in the current year were in opposite direction. This indicated towards the prevalent of threshold temperature above or below of which the responses become less sensitive to temperature or nonlinear to inverted U shaped relationship (Paulsen et al., 2000; D’Arrigo et al., 2004; Yadav et al., 2004a; Camarero & Gutiérrez, 2007; Kullman, 2007). The temporal trend in minimum and maximum temperature in the area is in opposite direction; hence, the different response could be result of this.

Different than the *A. spectabilis*, the growth of the *B. utilis* at SNP is mainly limited due to moisture stress during spring season just before the growth start or at the beginning of the growth. The response is slightly different in east, central and western part of the country. The western part is more sensitive and responsive to both precipitation and temperature as compared to the eastern part. As western part receives more precipitation in winter season, it was also reflected in the response with a significant positive relationship between the growth and winter precipitation (snow accumulation). The positive relation between growth with the spring months or season’s precipitation and negative with the same period’s temperature indicates towards the temperature induced moisture stress (Sano et al., 2005; Thapa et al., 2013, 2014; Liang et al., 2014). When temperature increases in the spring without the sufficient rainfall, moisture lacks behind evapotranspiration demand creating moisture stress ultimately leading low growth. In very cold environment, it is expected that high temperature during summer months is favorable for the growth, provided that if there is no moisture limitation. From the analysis of instrumental precipitation data over Nepal, both winter (DJF) droughts (1974, 77, 85, 93, 99 and 2001) and Summer (JJA) droughts were observed in Nepal (1977, 82, 91, 92) (Sigdel & Ikeda, 2010). During these years, *B. utilis* showed below average growth with narrow tree rings or missing rings indicating that its growth influenced by drought or moisture stress. Photosynthetic rates of plants are generally temperature dependent, high temperatures during the growing season will enhance photosynthetic production for alpine and subalpine plants (Fritts, 1976; Holtmeier, 2009; Körner 2012; Wang et al., 2013). The response obtained with climate in this study is consistent with other studies carried out in the treeline forming *B. utilis* from Himalaya (Bräuning, 2004; Bhattacharyya et al., 2006; Tenca & Carrer, 2008; Dawadi et al., 2013; Liang et al., 2015), though different details exists. Some difference in climatic growth response obtained in the present study with that observed by Liang et al. (2014) is due to difference in data used (Local station vs CRU; length and representation) for response analysis. There are two explanations of the negative relationship between the growth and spring temperature. On the one hand, warm spring temperatures promote photosynthesis and respiration; however, roots are still too cool to be efficient in water uptake, inducing stress dehydration and loss of carbon reserves (Wang et al., 2013). On the other hand, in Himalayan region, there would be very low rainfall during this spring season, however air temperature would be high (Fig. 25 to 28). Hence, temperature induced moisture stress leads to the formation of narrow rings in the trees in the subsequent growth period. Ring width of birch growing near treelines of Dolpo region is highly correlated with summer temperature of the summer prior to growth (Bräuning, 2004). Bhattacharyya et al. (2006) reported that higher temperatures and less rainfall during pre-monsoon month's results in lower tree growth of *B. utilis* in eastern Himalaya, India. Dawadi et al. (2013) found a positive correlation between *B. utilis* growth and March–May precipitation and an inverse relationship with pre-monsoon temperatures at timberline sites in Langtang valley, LNP, Nepal Himalaya. Reduced pre-monsoon moisture availability is a primary growth-limiting factor for *B. utilis* at many timberline sites (SNP, LNP and MCA) of Nepal Himalaya with a high percentage of missing rings or narrow rings coincided in the years having dry and warm pre-monsoon seasons (Dawadi et al., 2013; Liang et al., 2014). *Betula* species from other regions were also sensitive and responsive with summer and winter season climate (Takahashi et al., 2003, 2005; Wang et al., 2013). From a study in lower distribution limit of *Betula ermanii* and the upper distribution limit of *Betula platyphylla* var. *japonica* in Mount Norikura, Japan, Takahashi et al. (2003) found that tree-ring widths of these two *Betula* species were positively correlated with the August precipitation of the current year. Tree-ring width of *B. platyphylla* var. *japonica* showed no correlation with temperatures in any month in its upper distribution limit (Takahashi et al., 2003). The tree-ring width of *B. ermanii* at timberline in Mount Norikura, central Japan was correlated negatively with winter temperatures, positively with summer temperatures (June–August), and negatively with summer precipitation (July–September) of the current year (Takahashi et al., 2005). From a study of climatic response of *B. ermanii* along an altitudinal gradient in the northern slope of Changbai Mountain, China, Wang et al. (2013) found that the low temperatures during previous June, July and during the dormant period (previous October to current May) and the high temperatures during current June, July and August would benefit the radial growth of *B. ermanii*. Similarly, abundant precipitation during growing season (previous June, July, September and current August), previous November and current May, would also facilitate the tree-ring growth (Wang et al., 2013).

In the present study it was found that the temperature is main limiting factor in cold treeline environment. However in dry sites, moisture is limiting factor. Hence, the null hypothesis that the tree growth at treeline is independent from climate was rejected and alternative hypothesis stating that at an altitudinal treeline limit the tree growth is positively correlated with temperature, i.e. the limiting factor for the growth is temperature, and in dry area moisture being the limiting factor, was accepted.

From overall analysis it can be seen that, in the Himalaya, the growth-response of treeline forming trees to climate change and variability is spatiotemporally different and not unidirectional as well as species-specific (Bhattacharyya & Chaudhary, 2003; Yadav et al., 2004a; Sano et al., 2005; Bhattacharyya et al., 2006, Borgaonkar et al., 2011; Gaire et al., 2011, 2014; Lv & Zhang, 2012; Dawadi et al., 2013; Kharal et al., 2014; Liang et al., 2014; Schickhoff et al., 2015). Some studies have reported that the radial growth of treeline conifers to be more responsive to temperature than precipitation. Moreover, the western and central Himalayan conifers were more responsive to winter and pre-monsoon temperatures, while the east Himalayan conifers were more responsive to summer temperatures (Bräuning, 2004; Sano et al., 2005; Bhattacharyya & Shah, 2009; Borgaonkar et al., 2011; Gaire et al., 2011, 2014; Schickhoff et al., 2015). However, very few studies have been carried out in broadleaves tree species for the generalization of the results for whole broadleved tree species in the Himalayas.

4.4 Regeneration and treeline dynamics with climate change

Observation and comparisons of tree species' regeneration status i.e. proportions of total tree, saplings and seedlings, and their spatio-temporal distribution in treeline ecotone provides an insight into treeline dynamics. In site level comparisons, regeneration of *Abies spectabilis* was good as compared to *Betula utilis* (Fig. 35). The densities of seedlings and saplings of *A. spectabilis* are higher than that of *B. utilis*. The relative proportions of tree, saplings and seedlings as well as seedling to sapling ratio revealed that there was poor regeneration of *B. utilis* as compared to that of *A. spectabilis*. However, plot level regeneration is different than this site level comparison. Among three sites, regeneration *A. spectabilis* in MCA is relatively better than other sites while *B. utilis* has better regeneration in RNP.

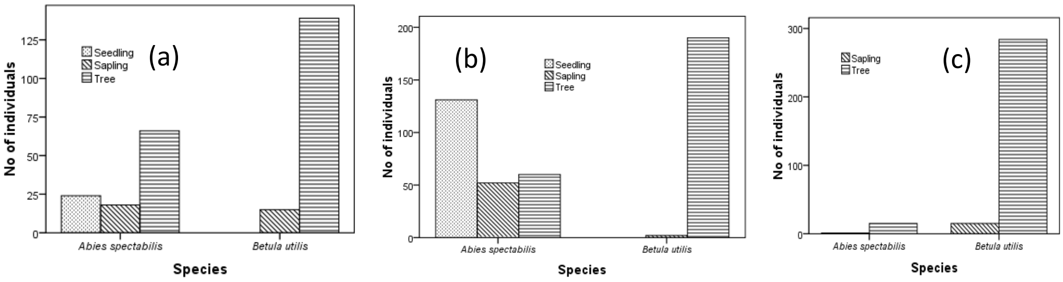


Figure 35: Comparison of proportions of seedling, sapling and tree individuals of Abies spectabilis and Betula utilis in the study area, Sagarmatha National Park (a), Manaslu Conservation Area (b) and Rara National Park (c), Nepal Himalaya.

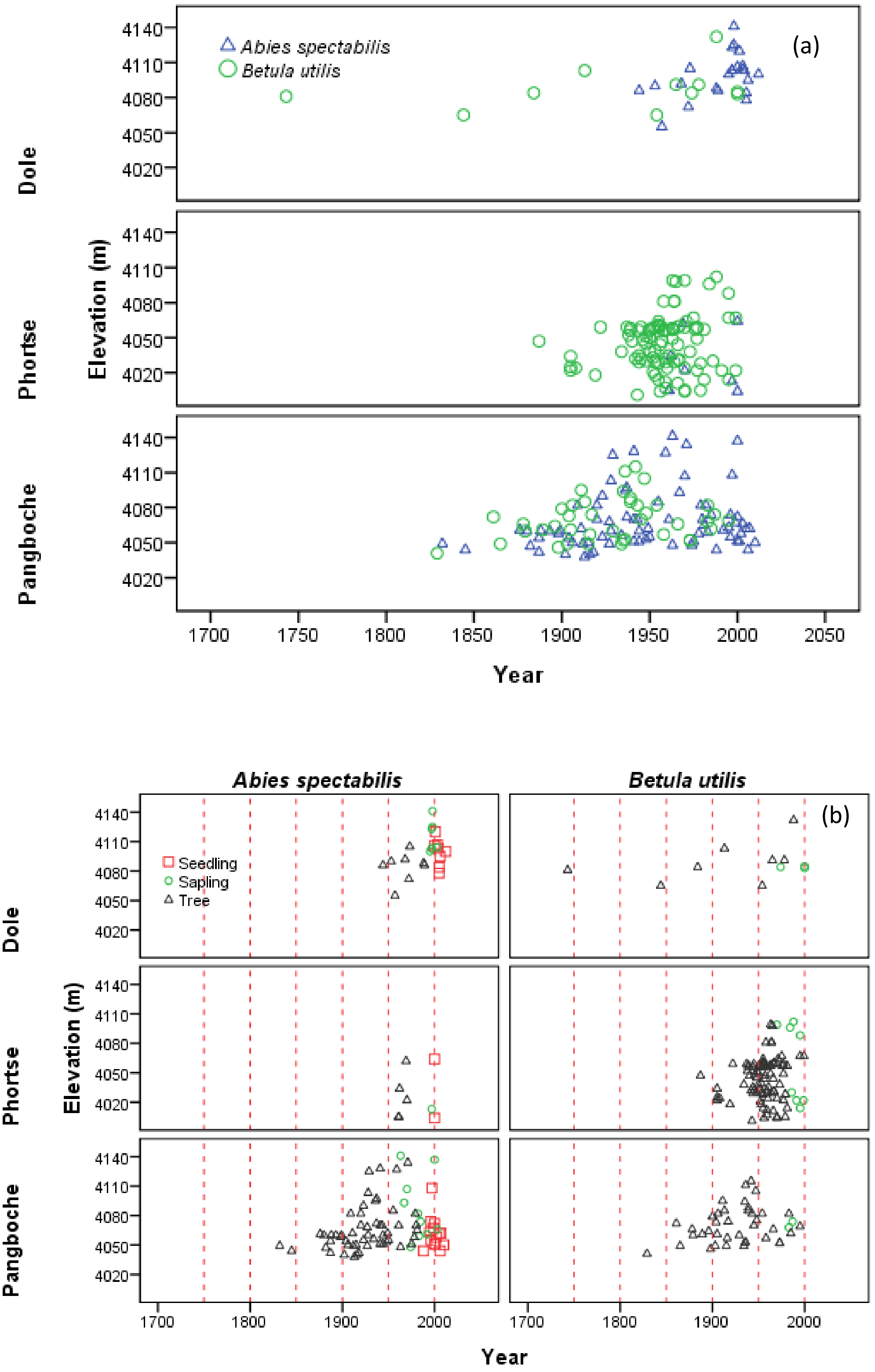


Figure 36: Sapatio-temporal variation in the recruitment and treeline dynamics in Sagarmatha National Park, Nepal Himalaya. Species level (a) and Species and individual category level (b).

Figure 36 depicts the spatio-temporal regeneration dynamics and treeline shifting in SNP area. In most of the plots and sites, the size parameters (age, diameter and height) were decreasing with increasing elevation. However, there exists site and species-specific nature in regeneration dynamics. Kolmogorov-Smirnov test reveals that there was significant difference in temporal pattern of recruitment among different sites and species ($\alpha = 0.05$). Similarly, there was significant difference in intra-sites temporal pattern of recruitment in majority sites ($\alpha = 0.05$). In majority of the sites, the *B. utilis* colonized earlier than that of *A. spectabilis*. However, in two sites (Pangboche and Dole of SNP) the position of *A. spectabilis* is at higher than that of *B. utilis*. There is very poor regeneration of *A. spectabilis* at upper part of most of the treelines while good regeneration was found towards the timberline. Poor regeneration of *B. utilis* in recent year is prevalent in most sites and all parts of treeline ecotone. Presence of the large seedlings and saplings of *A. spectabilis* in the lower reaches of the plots towards timberline or forest line indicates stand densification and infilling of existing treeline.

In most of the studied sites, there was species-specific and site-specific shifting patterns with little treeline shifting in the recent years. The average rate of upward shifting of *A. spectabilis* in SNP was 0.93 m/yr and *B. utilis* was 0.42 m/yr with recent stable position in majority sites. The upward shifting of *A. spectabilis* in Dole, Phortse and Pangboche of SNP was 1.08, 1.51 and 0.70 m/yr respectively while that for *B. utilis* was 0.35, 0.54 and 0.38 m/yr respectively. Irrespective of the plots, the average rate of treeline shifting of *A. spectabilis* in Pangboche since 1830s was estimated to be 0.7 m/yr with stagnant position since 1970s. There is very dynamics nature of *A. spectabilis* treeline in Dole with presence of only seedlings and saplings in whole D2 (Over 160 m long) plot and seedlings and saplings above tree individual in D1. The upward shifting of *B. utilis* treeline since 1830s in Pangboche was 0.38 m/yr with no upward treeline shifting since around 1950s. The treeline position in Phortse was stagnant since later part the 20th century. The *B. utilis* treeline in the Dole is shifting very little during past over 250 yrs. with almost stable position in recent years.

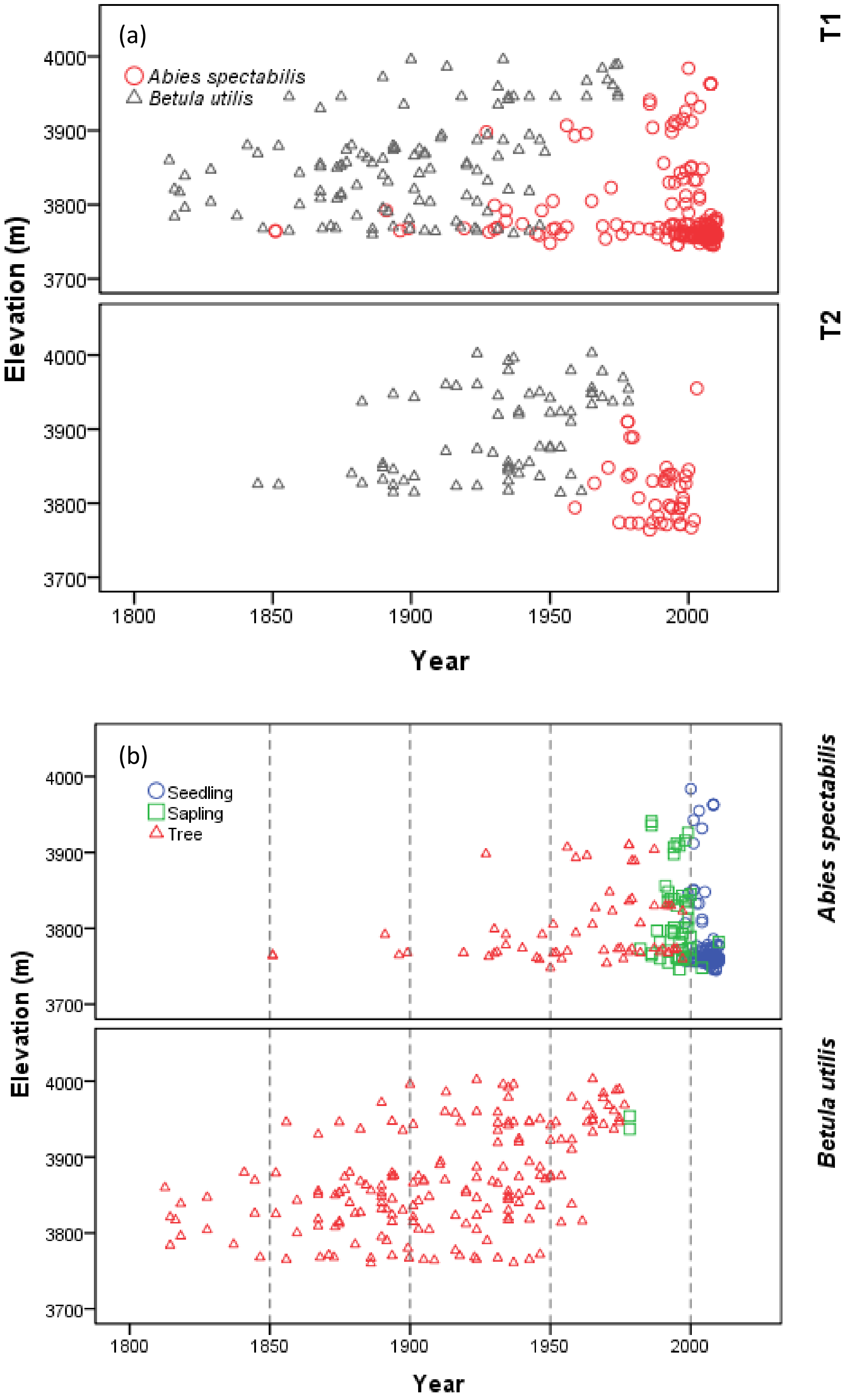


Figure 37: Sapatio-temporal variation in the recruitment and treeline dynamics in Manaslu Conservation Area, Nepal Himalaya. Species level (a) and species and individual category level (b). T1 and T2 are transects name used in this study area.

The spatio-temporal treeline shifting at MCA was assessed by analyzing elevation wise distribution of each individual of the *A. spectabilis* and *B. utilis* (Fig. 37). The graphs show a clear migration tendency of these species in the past (Fig. 37a). 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. 37a &b). Similarly, *B. utilis* colonized the area earlier than *A. spectabilis*. Seedlings of *A. spectabilis* species were found to be surviving about 80 m higher than trees indicating upward migration (Fig. 37b). Matured trees and young seedlings were mostly dominant at lower elevation indicating stand densification as well. 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 asl between 1810s and 1820s and at 3990 m asl during 1890s (Fig. 37b). *A. spectabilis* on the other hand made a treeline community around 1850 at 3765 m asl and reached 3907 m asl (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 m/yr (1.56 to 3.66 m/yr). The upward shifting of *A. spectabilis* was more pronounced in T2 with migration rate of 3.66 m/yr, while it was 1.56 m/yr in T1. In T1 average treeline shifting for whole ecotone was approx. 1.56 m/yr (1.36-1.75 m/yr) in recent decades which was higher above treeline (1.75) than that of below treeline (1.36). While in T2 was approx. 3.66 m/yr in recent decades which was lower in above treeline as compared to below treeline. This result showed that there was clear upward migration tendency of *A. spectabilis* with some spatial variation in this migration. The higher migrating rate at T2 is might be its patchy distribution at episodic recruitment. Though the exact rate of shifting of *B. utilis* was not calculated, there was a migration of *B. utilis* until around 1950s (Fig. 37 a & b). After that there is stabilization in the *B. utilis* position in the area (Fig. 37 a & b).

The elevation wise distribution of individuals of the *A. spectabilis* and *B. utilis* revealed that all size parameters were decreased with increasing elevation in RNP. The distribution of seedling, sapling and tree individuals along elevations shows a decreasing trend in the age with increasing elevation. However, the boundary of the treeline is sharp or abrupt.

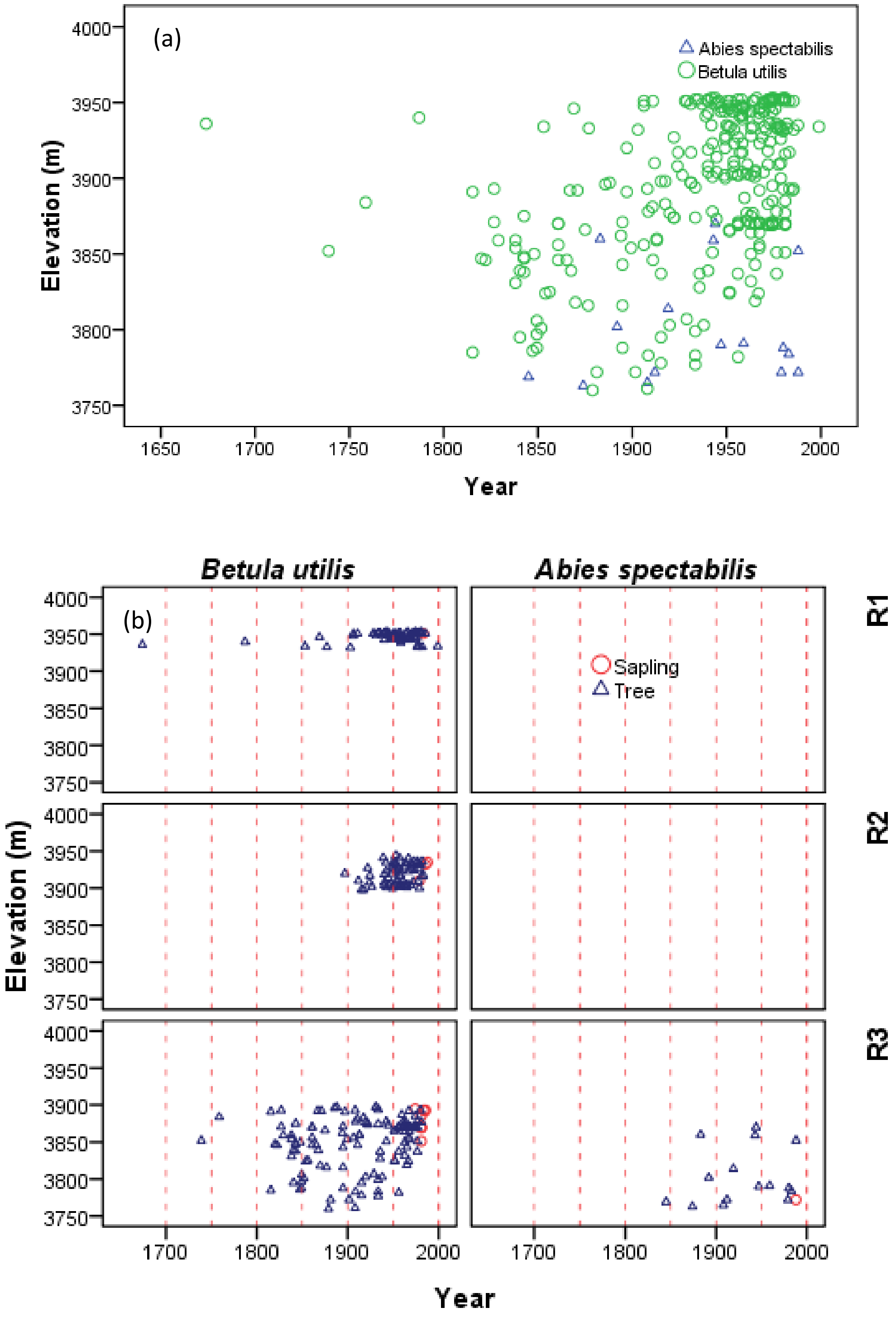


Figure 38: Sapatio-temporal variation in the recruitment and treeline dynamics in in Chuchemara, Rara National Park, Nepal Himalaya. Species level (a) and species and individual category level (b). R1, R2 and R3 are transects name used in this study area.

The spatio-temporal distribution of individuals of the *A. spectabilis* and *B. utilis* from the Chuchemara area of RNP shows that *B. utilis* colonized the area first and followed by *A. spectabilis* (Fig. 38). 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 all transects (Fig. 38a & b). No seedlings of both the species were recorded in all plots and available saplings were also close to the mature trees. The treeline ecotone of the area is stable for past several decades with sharp boundary. Depending upon the plots, the treeline position of the *B. utilis* is stable since past 50 to 150 years. Similarly, the *A. spectabilis* treeline is changed very little during past seven decades. This indicated that either this treeline already reached at climatic equilibrium position, or its lag response to climate change (Körner, 2012) or its upper boundary is controlled increasing aridity in the area (Sano et al., 2012) as well as to some extent by an anthropogenic disturbance factors like grazing, as observed in other areas (Shrestha et al., 2007, 2015; Speed et al., 2010).

Seedling establishment is an important factor dictating the altitudinal limits of treeline species (Hughes et al., 2009; Smith et al., 2009). Evidently, treeline rise depends on seeds produced at the local treeline rather than propagulae from more distant sources at lower elevations (Kullman, 2007). The boundary of *A. spectabilis* treeline in most sites is diffuse in form while that of *B. utilis* was abrupt. At and above the all treelines neither long-living krummholz nor sub-fossil wood of *A. spectabilis* and *B. utilis* was observed. This indicates the contemporary establishment history of these species. In many sites the seedlings and saplings were present closer to the position of upper tree individuals. However, some seedlings and saplings of *A. spectabilis*, probably due to global warming, have been thriving at much higher elevation than tree individuals in MCA and Dole site of SNP. In most sites of SNP and MCA, young seedlings of *A. spectabilis* were mostly dominant in the lower elevation also indicating stand densification of existing treeline ecotone. Similar to this study there was dominance of seedlings and saplings near timberline than upper treeline in Makalu-Barun National Park (MBNP) (Chhetri & Cairns, 2015); however, Shrestha et al. (2015) found seedlings abundant above the mean treeline in Lauribina, LNP.

Recruitment, critical determinant of the rate of forest or treeline shift (Camarero & Gutiérrez, 2007; Smith et al., 2009), 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). In most sites, the recruitment of *A. spectabilis* towards the lower reaches of the treeline ecotone was high during recent years which might have been facilitated by the warm temperature in the area and in the country (Cook et al., 2003; Sano et al., 2005). In spite of differences in plot level comparison, increased recent regeneration of *A. spectabilis* at treeline ecotone is a common findings of the treeline researches from the Nepal Himalaya; for example: Manang (Ghimire & Lekhak, 2007), LNP (Gaire et al., 2011; Schickhoff et al., 2015; Shrestha et al., 2015), Rolwaling valley, GCA (Schickhoff et al., 2015), MBNP (Chhetri & Cairns, 2015), and Tibetan site of Everest region (Lv & Zhang, 2012). Similarly, 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. Recruitment of *Picea schrenkiana* in Tianshan Mountains, northwestern China increased until the early 20th century (1910s) but then decreased with poor recruitment over the past several decades (1950–2000) (Wang et al., 2006). Batllori and Gutiérrez (2008) also observed past and recent synchronous recruitment trends of *Pinus uncinata* with climate change at the treelines in the Iberian eastern range of the Pyrenees. From overall comparision it can be seen that recruitment of species at treeline ecotones varies according to succesional stage, site condition and sensitivity towards environmental factors.

Similar to the observation by Shrestha et al. (2007), the boundary of *B. utilis* limit in most sites of present study treelines seems abrupt (tree individuals bordering treeline) with almost stable treeline position in recent years. In MCA and SNP, the regeneration of *B. utilis* during recent years is poor; however, in RNP there is continuous regeneration as revealed from size class distribution. Recently recruiting *B. utilis* seedlings are absent in most of the plots and sites, however saplings were present. Some studies from treeline of Nepal (Shrestha et al., 2007; Schickhoff et al., 2015) and Indian Himalaya (Rai et al., 2012) also found good recent regeneration of *B. utilis.* Schickhoff et al. (2015) found prolific regeneration in treeline of Rolwaling Valley in GCA with seedling establishment of *B. utilis, A. spectabilis,* and *Sorbus microphylla* to some extent far above the upper limit of adult trees. In spite of temperature warming in these areas, a stagnant upper distribution limit or treeline of *B. utilis* in the recent decades was observed in most of the study sites. Consistent with the observed trend in the other treelines (Kullman, 2001, 2002; Wang et al., 2006; Kullman & Öberg, 2009; Gou et al., 2012), spatio-temporal age distribution showed that there was regeneration as well as upward migration of the *B. utilis* in MCA till the end of 1960s and till 1970s in SNP. The peak in the tree establishment in MCA in the past corresponds to the warm episode in both winter and summer reconstructed temperature in the country (Cook et al., 2003). In RNP, though there is continuous regeneration, the upper distribution limit or treeline position of *B. utilis* is stable in the past 50 to 150 years depending upon the plots. The sharp boundary with recent stable position of this treeline indicates that, *B. utilis* treeline either shows lag response to climate change (Körner, 2012) or there might be an influence of anthropogenic activities in addition to climate (Shrestha et al., 2007; Aakala et al., 2014). Past studies using global data set indicated that diffuse treelines have exhibited an earlier, stronger response signal than the other treeline forms, with over 80% of diffuse treelines worldwide are advancing compared with 22% of abrupt, island or krummholz treelines (Harsch & Bader, 2011). Similarly, the advance in diffuse treelines initiated 10-40 years earlier than other treeline form (Harsch & Bader, 2011).

Trees inside treelines ecotone respond to climate change first by changing their physiognomy including population density, growth rate, only then by change in its position as such (Holtmeier, 2009; Körner, 2012). The treeline shifting with climate change, though not uniform & universal, is widely observed throughout the world. The rate of treeline shift found in the present study is consistent with the upward migration recorded in other studies from the Himalaya; for example, *Pinus wallichiana* (19 and 14 m per decade on south and north facing slope) in western Himalaya, India (Dubey et al., 2003), *A. spectabilis* in treeline of Samagaun region of the MCA (34 m per decade), central Nepal (Suwal, 2010), in Barun valley in MBNP (14 cm/yr), eastern Nepal (Chhetri & Cairns, 2015). During the past six decades, Shrestha et al. (2015) found stationary *A. spectabilis* treeline in Lauribina area of LNP and Pine treeline in Nagwal of Manang, central Nepal. Similarly, available model studies from Indian Himalaya using remote-sensing and repeat photography have reported increasing greenery in the treeline ecotone as well as upward shifting of the treeline ecotone at an alarming rate (Panigrahy et al., 2010; Bharti et al., 2012; Singh et al., 2012, 2013). In spite of shifting until mid-20th century, treelines from Tibet and other mountainous regions in China have been shifted very little in recent years (Wang et al., 2006; Liang et al., 2011; Gou et al., 2012; Lv & Zhang, 2012); however, stand densification is increasing consistently. 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 years. Similarly, Wang et al. (2006) found no an obvious upward shift of the *Picea schrenkiana* treeline in the central Tianshan Mountains over the last several decades with lack of new recruitment. Many studies from other mountains systems have reported increased tree density as well as shifting of treeline to higher elevation or latitude in response to environmental change; for example, *Pinus uncinata* in the Pyrenees Mountains (Camarero & Gutiérrez, 2004, 2007; Batllori & Gutiérrez, 2008), *Picea glauca* in SW Yukon, Canada (Danby & Hik, 2007), *Larix gmelinii* in the Putorana Mountains, northern Siberia (Kirdyanov et al., 2012), *Picea glauca*, *Picea mariana* and *Larix laricina*, *Abies lasiocarpa* near Churchill, Manitoba, Canada (Mamet & Kershaw, 2012), birch and pine forest lines in northernmost Norway (Hofgaard et al., 2013), *Betula pubescens* treelines in Torneträsk area in northern Sweden (Bogärt et al., 2011), *Pinus sylvestris* treeline in northeast Finland (Aakala et al., 2014), *Betula pubescens*, *Picea abies, Pinus sylvestris, Sorbus aucuparia*, and *Salix* species in the southern Swedish Scandes (Kullman, 2002; Kullman & Öberg, 2009). 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. Danby and Hik (2007) found an increased tree density as well as an advancement of Spruce (*Picea glauca*) treeline elevation by 65–85 m on south-facing slopes in south-west Yukon, Canada during the early to mid-20th century. Similarly, Kirdyanov et al. (2012) observed an upslope shift of the *Larix gmelinii* treeline position by approximately 30–50 m in altitude in the Putorana Mountains, northern Siberia during the last century. Bogärt et al. (2011) found 50% of studied treeline sites in Torneträsk area in northern Sweden being advanced in last century with an average treeline shift of 24 m upslope (0.2 m/yr), maximum treeline advance of 145 m (1.5 m/yr in elevation and 2.7 m/yr in actual distance), whereas maximum retreat was 120 m downslope. Öberg and Kullman (2012) found both upward (3 m/yr) and downward (0.4 m/yr) movement of *Betula pubescens* ssp. *czerepanovii* treelines in short temporal scale in Swedish Scandes. In northernmost Norway, the birch and pine forest lines advance northward by 156 and 71 m/yr, respectively since the early 20th century (Hofagaard et al., 2013). The birch treeline showed the most pronounced advance (340 m/yr), whereas the pine treeline showed very limited advance (10 m/yr). Aakala et al. (2014) observed a prominent stepwise advance of the *Pinus sylvestris* treeline in northeast Finland with slow increase in treeline in the beginning of 20th century (0.5 m/yr) and more rapid advance later (1.4 m/yr).

4.5 Climatic response of regeneration and treeline dynamics

Figure 39 depicts the relationship between tree establishment or regeneration and climate in the SNP area. The regeneration-climate relation is species-specific as well as site dependent. The regeneration of *Abies spectabilis* was positively favored by the high temperature in both winter and summer if there is sufficient moisture. There is a significant positive relationship ($r > 0.4$, $p < 0.01$-0.05) between the regeneration of *A. spectabilis* in the Pangboche SNP and monthly mean temperature of the most of the months and monthly precipitation of March (Fig. 39a). Almost similar response was obtained between the regeneration of *A. spectabilis* at Dole-Phortse combine with climate (Fig. 39b). However in month-to-month comparisons, there exists some variation in the response between sites which may be associated with variation in the microclimate, topography and other feedback mechanisms.

Regeneration-climate relation of *Betula utilis* at treelines in SNP was spatio-temporally differentiated (Fig. 39c to f). Until 1990s to which regeneration was present, the high monthly temperatures and precipitation in the summer and autumn months i.e. May to October positively favored the regeneration of *B. utilis* in Pangboche SNP with a significant positive relationship ($r > 0.4$, $p < 0.05$) between the regeneration and monthly mean temperature of July to October. The lack of recently established seedlings and saplings of *B. utilis* in treelines leads the relation to be weak as well as dominantly negative with climate parameters, when we consider for whole period. Different from Pangboche, the regeneration in Dole was negatively influenced by high monthly mean temperature of July.

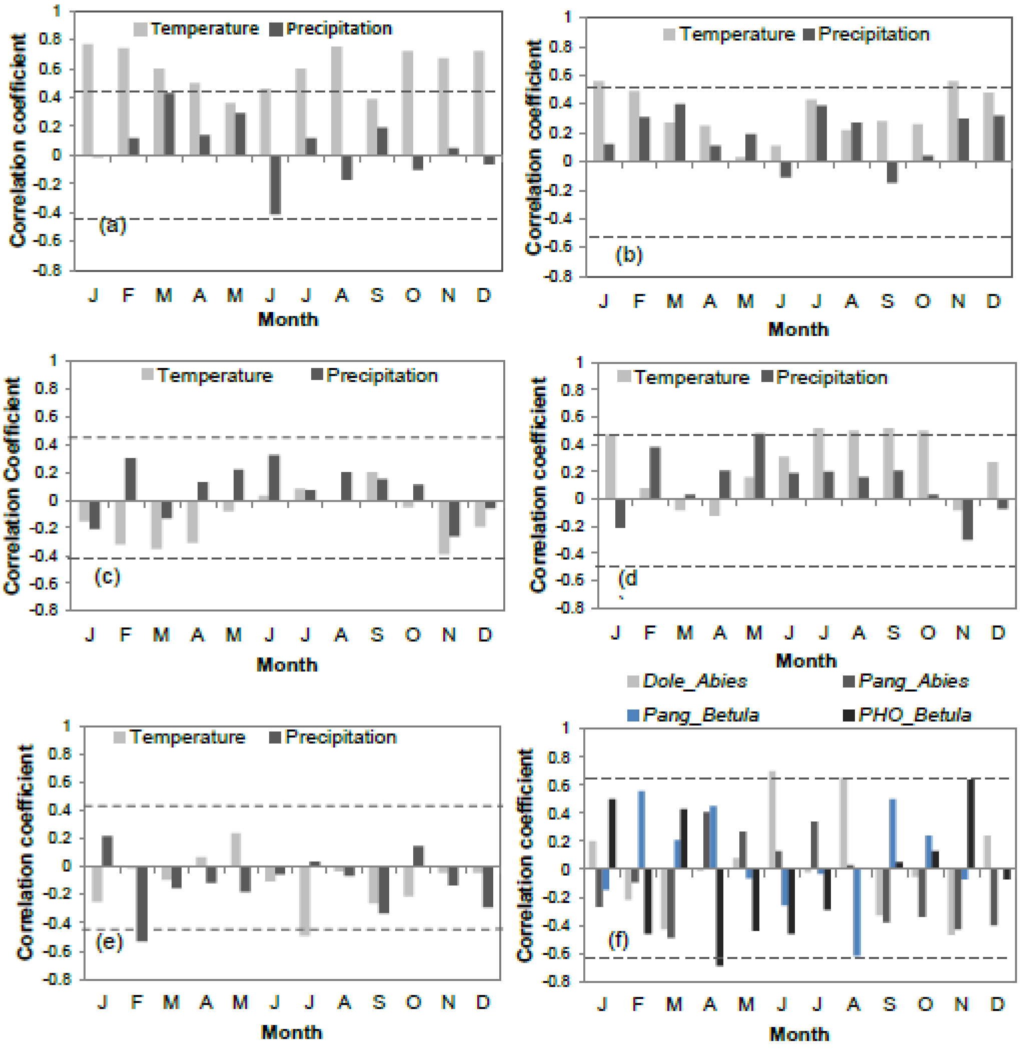


Figure 39: Correlation (Pearson's correlation) between the regeneration of *Abies spectabilis* and *Betula utilis* with monthly climate data in treelines of Sagarmatha National Park, Nepal Himalaya. The horizontal dash line indicates correlation coefficient significant at 95% or more confidence level. Regeneration-climate (CRU) relation of *Abies* in Pangboche (a) and Dole-Phortse (b); Relation with *Betula utilis* in Pangboche in different period: 1900-1990 (c) and 1900-2010 (d) period and in Phortse (e); Relation between regeneration and Chaurikharka stations precipitation data (f). J to D stands for the short form of the months starting from January to December.

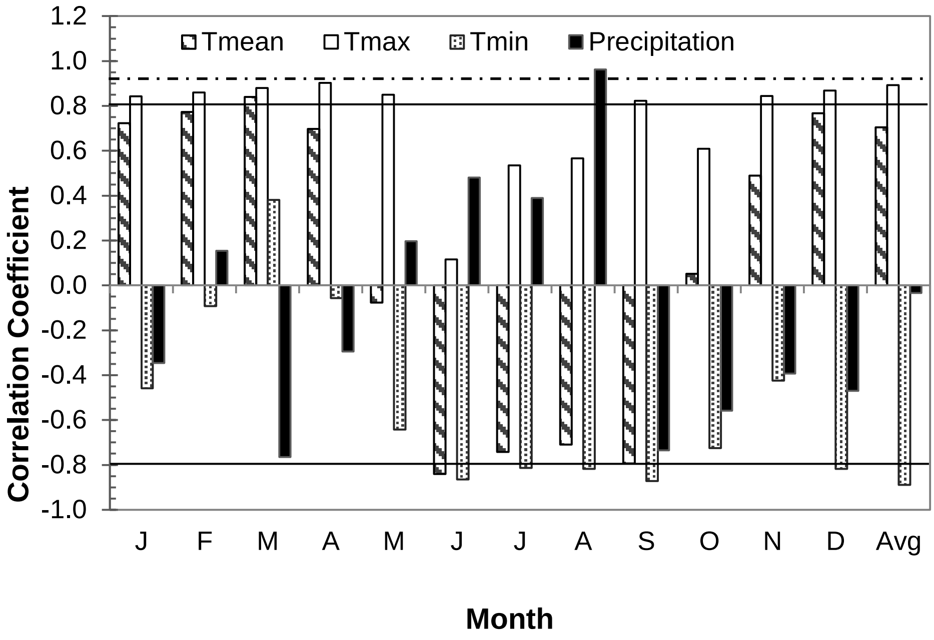


Figure 40: Relationship between regeneration *Abies spectabilis* with monthly climate in Manaslu Conservation Area, Nepal Himalaya; The black horizontal line indicates a significant correlation at the 95% confidence limit for a two-tailed test and dashed horizontal line indicates a significant correlation at the 99% confidence limit for a two-tailed test. For climatic influence on the regeneration of the *A. spectabilis* with climatic window of 12 months of current years as well as annual average of temperature or annual sum of precipitation are used.

Regeneration of the *A. spectabilis* in the MCA was favoured positively by the above-average monthly maximum temperature during most of the months and above-average precipitation during dry warm summer months (Fig. 40). The relationship between regeneration and monthly maximum temperature of most months of the current year was positive and statistically significant ($r > 0.8$, $p < 0.05$) while the relationship was negative but significant with the monthly minimum temperature of June–September of the current year ($r > -0.7$, $p < 0.05$) (Fig. 34). The relation between regeneration and precipitation in August ($r = 0.96$, $p < 0.01$) was positive and statistically significant (Fig. 40). It is also evident from Figure 40 that the growth and regeneration of *A. spectabilis* is more sensitive to minimum or maximum temperature rather than average temperature because correlation with these is more positive or negative than average. Similarly, there is opposite relationship between the minimum and maximum temperature which indicates the prevailing of threshold level effect in the response.

There are no seedlings and very few saplings of *B. utilis* in the recent years covered by local climatic data in MCA. On the other hand, there is weak relationship between the local station based climatic data and CRU climate data. Therefore, climatic response of regeneration of *B. utilis* in the area was not calculated.

The regeneration climate relationship from RNP revealed that the regeneration in this area is more sensitive towards the precipitation as compared to temperature (Fig. 41). There was a significant positive relationship ($r > 0.66$, $p < 0.05$) between the regeneration of *A. spectabilis* and Jumla stations' precipitation of March, July and December months and significant negative relationship between monthly average temperature of the May and July months. Almost similar response was obtained with local station data and CRU grid climate data (Fig. 41). As May is dry month in the area, the negative relation may be associated with moisture stress. However, as July is summer month with monsoon precipitation, however, the reason of negative relation with this month could not understand. One reason could be high cloud coverage in this months could blocks the solar radiation and decrease the temperature which ultimately negatively affects the survival. As very few *A. spectabilis* individuals were present in the plots, the response might be different in the treeline dominated by this species.

The relationship between the regeneration of *B. utilis* in treeline of RNP and climate is weak as well as negative with both the climatic variables. There was a significant negative relationship between the regeneration of *B. utilis* and monthly temperature of the summer months (Fig. 41), which may be due to moisture stress leading mortality of the seedlings as observed in *A. spectabilis* too. A negative relationship between both climatic variables is less common and difficult to explain. The temperature in the area is increasing consistently but precipitation is decreasing together with decreasing regeneration. This moisture stress might be responsible for poor recent regeneration ultimately leading the relationship be negative. Another reason could be due to the some uncertainty in age estimation based on age-diameter relationship. Response is slightly different in different age estimation methods (Fig. 41). Census sampling based age estimation could give more accurate picture on relationship between regeneration of *B. utilis* and climate. Other reason is that non-climatic factor might be modulating the climatic response and also controlling the recent regeneration. Hence, further study considering both climatic and non-climatic factor is required for better understanding about the response.

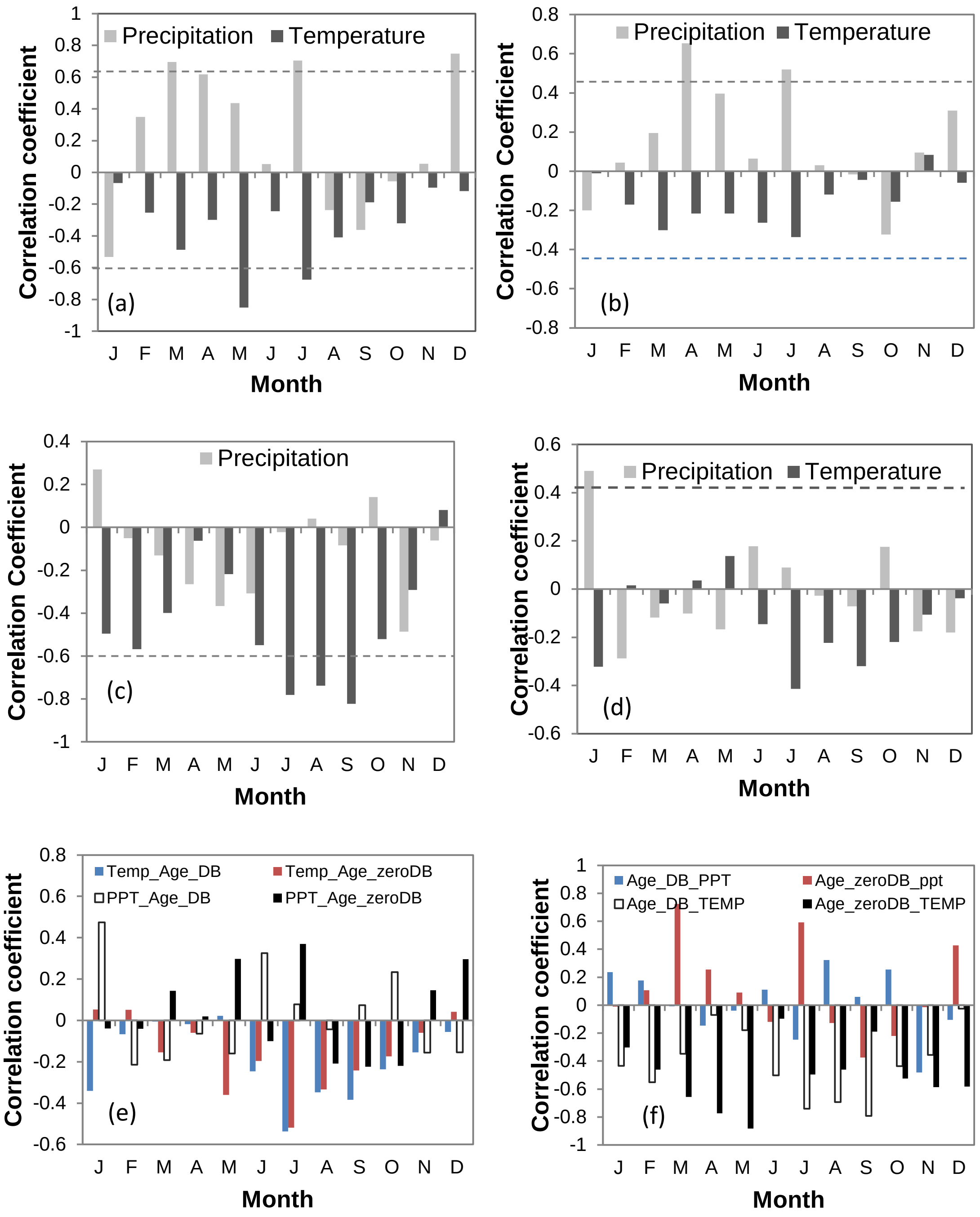


Figure 41: Relationship between regeneration of *Abies spectabilis* in Chuchemara in Rara National Park with monthly climate of Jumla (a), monthly CRU climate (b); *Betula utilis* with Jumla climate (c) and with CRU (d), *Betula utilis* with alternative age estimation with Jumla climatic data (e) and CRU data (f) and; The black dashed horizontal line indicates a significant correlation at the 95% or more confidence limit for a two-tailed test.

Treeline shows different structural and physiognomic responses to climate change in the different spatio-temporal scales (Holtmeier & Broll, 2005; Holtmeier, 2009; Körner, 2012). The sensitivity of treelines to climate change varies not only with local and regional topographical conditions but also with treeline forms (Holtmeier & Broll, 2005, 2007; Harsch & Badar, 2011). In treelines ecotones, the climate conditions that facilitate the radial growth may be similar to those conditions conductive to recruitments (Dang et al., 2009; Lv & Zhang, 2012; Zhao et al., 2013), or the two processes of recruitment and growth may respond differently to climatic factors (Daniels & Veblen, 2004; Wang et al., 2006). In the present study, the climatic factors that limit or favour radial growth of *Abies spectabilis* and *Betula utilis* were almost similar to that for regeneration of same species in some sites while different in other sites; however different details exists in month-to-month comparisons and site-to-site comparisons. Generally, the regeneration of the *A. spectabilis* is favoured by a high both winter and summer temperature in eastern and central Nepal. Germinant of the *A. spectabilis* are also more sensitive and responsive to the temperature as compared to precipitation. High precipitation during the spring and summer season is also beneficial for the regeneration of *A. spectabilis*. However in some dry sites in western Himalaya high moisture favors the survival of the *A. spectabilis* seedlings. Regeneration of *B. utilis* is also favoured by both temperature and precipitation. The different details in the response among the sites may be associated with influence of local topographical conditions and tree age (Carrer & Urbinati, 2004; Wang et al., 2009; Mérian & Lebourgeois, 2011).

Studies have reported the sensitivity of the fir recruitments with temperature, moisture and drought conditions (Liang et al., 2011; Lv & Zhang, 2012; Gaire et al., 2014). In treelines of MCA, regeneration of *A. spectabilis* is favored by a high temperature throughout the year with sufficient moisture during summer season. In SNP, high temperature and precipitation positively favoured the regeneration of *A. spectabilis*. In contrast, western Nepal is relatively dry which is reflected in the response because in RNP a moist and cool year favoured the regeneration of *A. spectabilis*. The *A. spectabilis* recruitments were positively correlated with monthly mean air temperatures in June and September and with PDSI in June at the timberline in the Tibetan side of the Everest region (Lv & Zhang, 2012). Consistent to present study at SNP, *Abies georgei* var. *smithii* recruitment in a treeline on the southeastern Tibetan plateau was sensitive to both summer and winter temperatures with significant positive correlation with them (Liang et al., 2011). A transplant study conducted on the Tibetan plateau revealed that early-season freezing events would be the major limiting factor determining mortality of *A. georgei* seedlings above the current treeline (Shen et al., 2014). Zhao et al. (2013) found significant positive correlations between recruitment of *Abies faxoniana* in the treeline of Min Mountains, southwestern China and monthly mean temperatures for the current April, July and September but no significant correlations with monthly precipitation during the last 60 years. Wang et al. (2006) found that both temperature and precipitation influence positively for recruitment of *Picea schrenkiana* in the central Tianshan Mountains, northwestern China. Consecutive years of high minimum summer temperatures and high precipitation during spring mainly influenced for the *Picea schrenkiana* recruitment (Wang et al., 2006). Camarero and Gutiérrez (2007) found that a high May, August, and September minimum temperatures and high April precipitation were positively associated with recruitment of *Pinus uncinata*, whereas high maximum April and June temperatures were negatively associated with recruitment at treeline in Iberian System, NE Spain. There might be threshold effect on recruitment at treeline ecotone rather than a linear effect (Camarero & Gutiérrez, 2007).

In present study area, there is a consistent increasing temperature but weakening precipitation (Fig. 25 to 28), with high intra annual variability (Salerno et al., 2015). In spite of this warm climate, the moisture stress due to weakening precipitation and increasing high interannual variability might be limited the new seedlings and saplings establishment. Schickhoff et al. (2015) found significant positive correlations of seedling/sapling abundance with soil moisture for *A. spectabilis*, *B. utilis*, and *Rhododendron campanulatum*, and with soil temperature for *A. spectabilis*, *B. utilis*, and *Sorbus microphylla*. Another study from a treeline of trans-Himalaya reported that the distribution of seedlings and saplings of *B. utilis* depend on canopy cover and its seedlings could not establish under their own closed canopy even if they produced viable seeds (Shrestha et al., 2007). In mature stands, partial canopy opening may induce seedling establishment and hence continuous regeneration of *B. utilis* (Shrestha et al., 2007). Some parts of this spatial difference and weak regeneration-climate response of *B. utilis* may be explained by temporal change in sensitivity, some uncertainty in the age estimation using regression models, or influence of non-climatic abiotic and biotic factors in the regeneration of the birch seedlings (Shrestha et al., 2007). Further studies are desirable to separate the effects of climate on the two main processes determining tree recruitment, i.e. seed production (e.g., masting) and seedling establishment.

Relationships between regeneration, treeline shifts and climate change may be more complex because climate may affect tree recruitment and treeline advance rate in different ways (Camarero & Gutiérrez, 2004; Wang et al., 2006; Kirdyanov et al., 2012; Körner, 2012). A treeline ascent implies several consecutive processes: production of viable seeds, dispersal, and availability of adequate regeneration sites, germination, seedling survival and persistence until the individual reaches adulthood (Wang et al., 2006; Kullman, 2007; Smith et al., 2009; Körner, 2012). Climate variability affects all these sequential stages, but the same climatic variable can enhance one of these processes while inhibiting another one (Camarero & Gutiérrez, 2004; Wang et al., 2006). At a global scale, treelines are considered to be constrained primarily by growing season temperature (Körner & Paulsen, 2004; Körner, 2012), however, winter temperature has also played some role in many sites (Harsch et al., 2009). Sustained and favorable climatic conditions during establishment and particularly during recruitment phase are crucial for controlling treeline dynamics (Wang et al., 2006; Smith et al., 2009; Mamet & Kershaw, 2012) because one bad year is sufficient for killing the germinant established in many favorable years. At many alpine treeline ecotones, both winter and summer temperatures are often key constraints on tree recruitment and treeline dynamics (Harsch et al., 2009; Liang et al., 2011). However, temperature warming may not necessarily lead to unidirectional changes in treeline position (Camarero & Gutiérrez, 2004; Körner, 2012).

Past studies have shown that one and the same climatic fluctuation does not lead to the same pattern and magnitude of birch treeline change everywhere (eg. Kullman & Öberg 2009; Virtanen et al. 2010; Elliott & Kipfmueller 2011), and high inter-annual climatic variability and snow cover phenology could have a vital role for differential birch treeline dynamics (Oberg & Kullman, 2012; Rai et al., 2013). In addition, non-climatic local site conditions (Wang et al., 2012), species' traits, plant–plant interactions and feedback effects (Bekker, 2005; Danby & Hik, 2007; Batllori & Gutiérrez, 2008; Batllori et al., 2009; Schickhoff et al., 2015), disturbance (Speed et al., 2010, 2011; Munier et al., 2012; Shrestha et al., 2015) may modulate the climatic response and control regeneration and treeline dynamics.

Climatic response of regeneration and treeline dynamics may vary with treeline forms. Studies revealed that abrupt or krummholz treelines are less responsive to climate change than diffuse treelines (Harsch et al., 2009; Harsch & Badar, 2011; Liang et al., 2011; Körner, 2012). This was also observed in the present study. It is speculated that diffuse treelines may be strongly limited by growing season temperature and hence particularly responsive to overall temperature increases. It is hypothesized that the upslope movement of diffuse treelines in the Nepal Himalaya would be expected to be proportional to both winter and summer warming as reported by Harsch et al. (2009), and that trees would be expected to grow more densely in response to warming. The diffuse treelines of MCA and some sites in SNP are changing with climate change, while abrupt treeline in RNP is not much changed although there is significant temperature warming. However, this study found stand densification as common response to climate change in many treeline sites of the study areas in Nepal Himalaya. Hence, this study rejects the null hypothesis that treeline position and stand structure are independent of climate change, it rather accepts the alternative hypothesis that treeline position and or stand structure are changing with climate change in the study area.

In agreement with other studies worldwide, mainly temperature is the dominant controlling climatic factor for the regeneration, growth and treeline dynamics in the studied treelines. However, in dry sites moisture is leading climatic factor controlling these events. In the present study at the upper treeline in the Nepal Himalayas, the establishment of the *A. spectabilis* is also controlled by both winter and summer climatic events. In comparison to *B. utilis*, the growth and regeneration of *A. spectabilis* is more sensitive to temperature than precipitation. The high regeneration of the seedlings and saplings of *A. spectabilis* in lower reaches of treeline towards the timberline can be explained by the significant positive relationship between regeneration and climate. However, very few number of seedlings and saplings of *A. spectabilis* and *B. utilis* were present at the upper reaches of the plots near tree species limits. Seed dispersal factors (quantity of seeds produced, the adaptations for dispersal, the availability of appropriate dispersal agents and the distances over which seeds must be transported) are major determinants of the success and speed of species migration along environmental gradients (Price et al., 2001). Lack of seed dispersion is not limiting for recent seedling establishment and treeline shifting because some seedlings and saplings are growing up to a few hundred meters above the tree individuals in this study and in other treeline areas of Nepal Himalaya (Gaire et al., 2011, 2014; Schickhoff et al., 2015; Shrestha et al., 2015). Despite the availability of suitable sites for establishment and the presence of reproductive individuals, many of these treelines are stable in past many years with reduced rates of recruitment of *B. utilis* in recent decades in most sites and *A. spectabilis* in some sites. Therefore, this indicated that the studied treelines are either already in equilibrium position with climate, or showing lag response to climate change (Körner, 2012) or warming may have exerted a negative non-linear effect on recruitment (Camarero & Gutiérrez, 2007), resulted from moisture stress due to weakening precipitation (Fig. 25 to 28). In addition to this, the regions at and above the treeline ecotone are commonly used as summer grazing area in the Himalayas. In treeline of MCA and Dole area of SNP where the grazing pressure is less intense, treeline dynamics is prominently seen. The treelines of RNP area are abrupt in form directly bordering by alpine grassland generally without shrub scrubs. In addition to nonlinear threshold effect of warming temperature and weakening precipitation, the non-climatic factors like grazing and herbivory, micro-topography, the completion with dense krummholz *Rhododendron* trees and shrubs scrub, probable allelopathic effects, competitive ability of treeline forming species might be modulating the beneficial impacts of temperature warming, eventually controlling the recent seedlings establishment and treeline shifting (Cairns & Moen, 2004; Shrestha et al., 2007; Batllori et al., 2009; Munier et al., 2010; Speed et al., 2011; Rai et al., 2012; Wang et al., 2012; Zhao et al., 2013; Chhetri & Cairns, 2015; Schickhoff et al., 2015; Shrestha et al., 2015). Shrestha et al. (2015) suggested that stationary *A. spectabilis* treeline, even in warming temperature in LNP area, is regulated by non-climatic factors, particularly grazing. Schickhoff et al. (2015) found a negative correlation between abundance and density of *Rhododendron campanulatum* and recruitment of other tree species, due to competition with dense foliation of evergreen *Rhododendron* as well as probable allelopathic effects. In spite of favorable climate, the dense krummholz belt can be an effective barrier for upslope migration of other tree species (Batllori et al., 2009; Schickhoff et al., 2015). Shrestha et al. (2007) found stable *B. utilis* treeline due to anthropogenic pressure, mainly grazing and browsing.

An increasing number of studies have demonstrated that tree population density at treelines can respond quickly to rising temperatures (Camarero & Gutiérrez, 2004; Kullman 2007, Liang et al 2011; Körner, 2012) compared to the changes in treeline position because of the great longevity and phenotypic plasticity of tree individuals (MacDonald et al., 1998; Lloyd, 2005; Körner, 2012). If temperature is the primary and dominant driver for both recruitment and growth, these processes should be positively synchronized (Fajardo & McIntire, 2012). Some previous studies at treelines found concurrent synchronies (MacDonald et al., 1998; Batllori & Gutiérrez, 2008) and lagged synchronies of tree growth and regeneration in both positive and negative directions with climate change (Fajardo & McIntire, 2012). Present study did not find perfect synchrony; however, regeneration of *A. spectabilis* in some sites were synchronous with climate warming, but *B. utilis* regeneration is asynchronous or lag synchronous as very few seedlings and saplings are found in recent warming decades.

In spite of the regeneration of *A. spectabilis* above the existing treeline in many sites, the pace of future treeline shifting with climate change may not necessarily be the same because a seedling takes many years from establishment to reach its tree height (at treeline, *A. spectabilis* took more than 30 years to reach 2 m height) and developed into a forest stand (Lloyd, 2005; Shrestha et al., 2015). On the other hand, there were no seedlings of *B. utilis* at and above the many treelines. Even if they establish now, it will take several decades for newly established *B. utilis* seedlings to develop and form new treeline. As *A. spectabilis* in the treeline is more responsive to temperature change, an advance of this at natural treeline of the Himalaya with climate change may continue if a long-term warming trend stimulates growth frequently enough even in cooler years or if low temperature events/periods which limit growth and regeneration are insignificant or if there would not be water deficit in plants which could offset the expected positive effects from temperature increase in tree establishment, growth and the upslope advance of treeline (Paulsen et al., 2000; Daniels & Veblen, 2004; Wang et al., 2006; Kullman & Öberg, 2009). In case of *B. utilis*, Liang et al. (2014) reported that birch treeline of the Himalaya is a rare case of a drought-induced alpine timberline and Himalayan birch at its upper distribution boundary is increasingly at risk of survival. Though the moisture stress during spring season affects the growth of *B. utilis*, from field observation, large number of recently recruiting *B. utilis* seedlings and saplings above the tree individuals were found in the treelines of Kanchanjungha Conservation Area, eastern Nepal, and fair regeneration at timberline in RNP and Api-Namapa Conservation Area in mid and far-western Nepal (Field observation, 2014). Based on the field observation, it is reasserted that *B. utilis* trees have been withstanding past several extreme climatic events and hence will continue (Schickhoff et al., 2015). In addition to climate, *B. utilis* treelines could be influenced by non-climatic factors like grazing and browsing. Therefore, if the situation will ameliorate with sufficient moisture and minimization of grazing pressure including other site specific controlling mechanisms, the *B. utilis* treeline position will change with climate change but with some lag periods. Studies, based on observation and modeling, not only indicated a linear trend in temperature and precipitation, but also an increase in extreme events in the Himalayan region (Krishnamurthy, 2009; Shrestha et al., 1999, 2012; Kulkarni et al., 2013; del Rio et al., 2013; IPCC, 2014; Panday, 2014; Agarwal et al., 2015; Sheikh, 2015). Similarly, bioclimatic modeling studies using different IPCC future scenarios have indicated that, if current warming continues, climate conductive for treeline shifting will reach very soon in the Himalayas and then treeline will move upward (Rai et al., 2012; Singh et al., 2013; Schickhoff et al., 2015). With the supportive evidence of differential life history, regeneration condition, treeline dynamics, species-specific response of these two treeline species with climate change, it is anticipated that, in addition to treeline position, the community structure in the studied treelines in Nepal Himalaya is going to change, if current climate change and response pattern continues. Further studies incorporating soil nutrients and characteristics, grazing exclusion and transplantation experiment, masting in seed production, testing of growth or carbon limitation in the treeline formation, competition between seedlings and shrubs will be beneficial for better understanding of response of treeline and their dynamics with future climate change.

4.6 Dendroclimatic reconstruction

4.6.1. Climate reconstruction: eastern Nepal (Sagarmatha National Park)

Climate of the SNP regions was not presented in present study, in spite of theoretically possible. Though there is significant correlation between the growth and climatic data of some seasons, the relationship is not strong enough ($r < 0.4$) to be reliably used for climate reconstruction. As we used CRU climatic data for the growth-climate model development, the EPS value of the chronologies passed the threshold mainly up to the period covered by CRU data, and hence reconstruction could not go beyond. For the reasons mentioned above, climate reconstruction of the SNP region was not performed.

4.6.2. Climate reconstruction: central Nepal (Manaslu Conservation Area)

In accordance with the growth-climate response analysis in the preceding section of climate-growth response, May–August temperature can be theoretically reconstructed for MCA region. 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:

$$T_{MJJA} = a \text{ RW} + c$$

Where, T_{MJJA} 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 and also using leave-one-out cross validation. It was found that the temperature transfer function was highly significant at 1% (Table 12).

Table 12: Validation statistics of regression model between tree-ring chronology of *Abies spectabilis* and monthly mean temperature of May-August from Manaslu Conservation Area, Nepal Himalaya

Model R	R Square	Adjusted R Square	Std. Error of the Estimate	F	Sig.	RE
0.554[a]	0.307	0.282	0.798	12.411	0.001[a]	0.222

a. Predictors: (Constant), Standard chronology   b. Dependent Variable: MJJA observed temp

Finally, mean May–August temperature for 229 year long period from 2010 AD extending back to 1782 AD was reconstructed. However in the graph, only the period of the chronology exceeding the EPS threshold (1867-2010) was shown (Fig. 42). The reconstructed May–August temperature shows several warm and cool periods. This also shows the slight warming at the end of 20th century (Fig. 42).

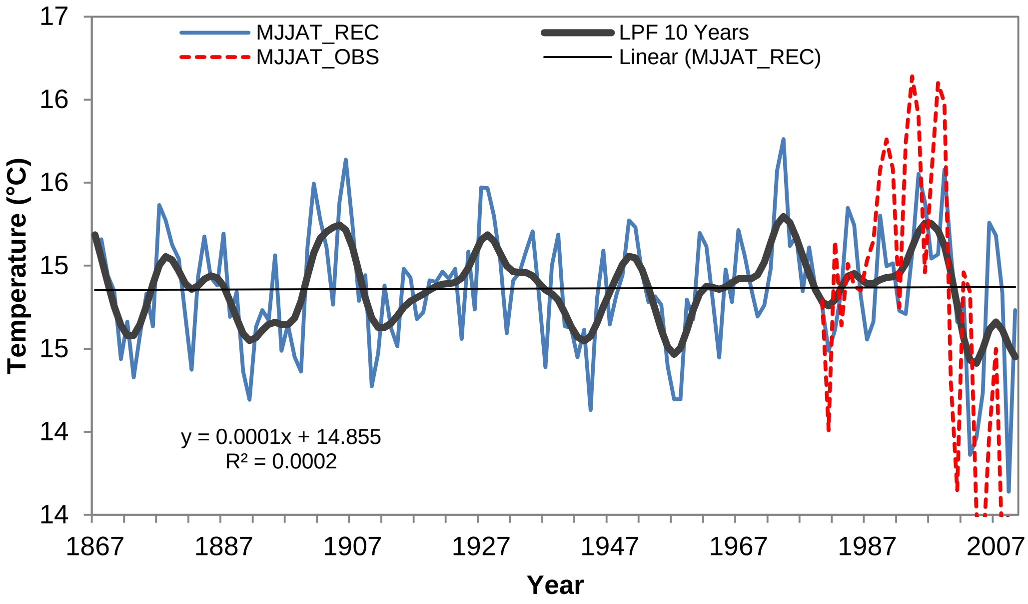


Figure 42: Tree-ring width based MJJA reconstructed temperature for Manaslu Conservation Area, Nepal Himalaya. The 10-year low pass filter (LPF) to the reconstruction and observed data are also shown by thick solid line.

Abies spectabilis is identified a species with high dendrochronological potential as it meets the criteria of a low autocorrelation, a high mean sensitivity and a high standard deviation that are considered as a basis to have a good potential for dendroclimatological studies (Fritts, 1976). Although the calibration is based on short (30 yrs.) climate data record (1980-2009), 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., 2013).

The spatial correlation of the observed and reconstructed temperature with CRU TS3.22 grid temperature shows no significant correlation (Fig. 43). This indicates that the climate of the study area in MCA is more influenced by microclimate rather than broader climatic pattern in the Himalayas.

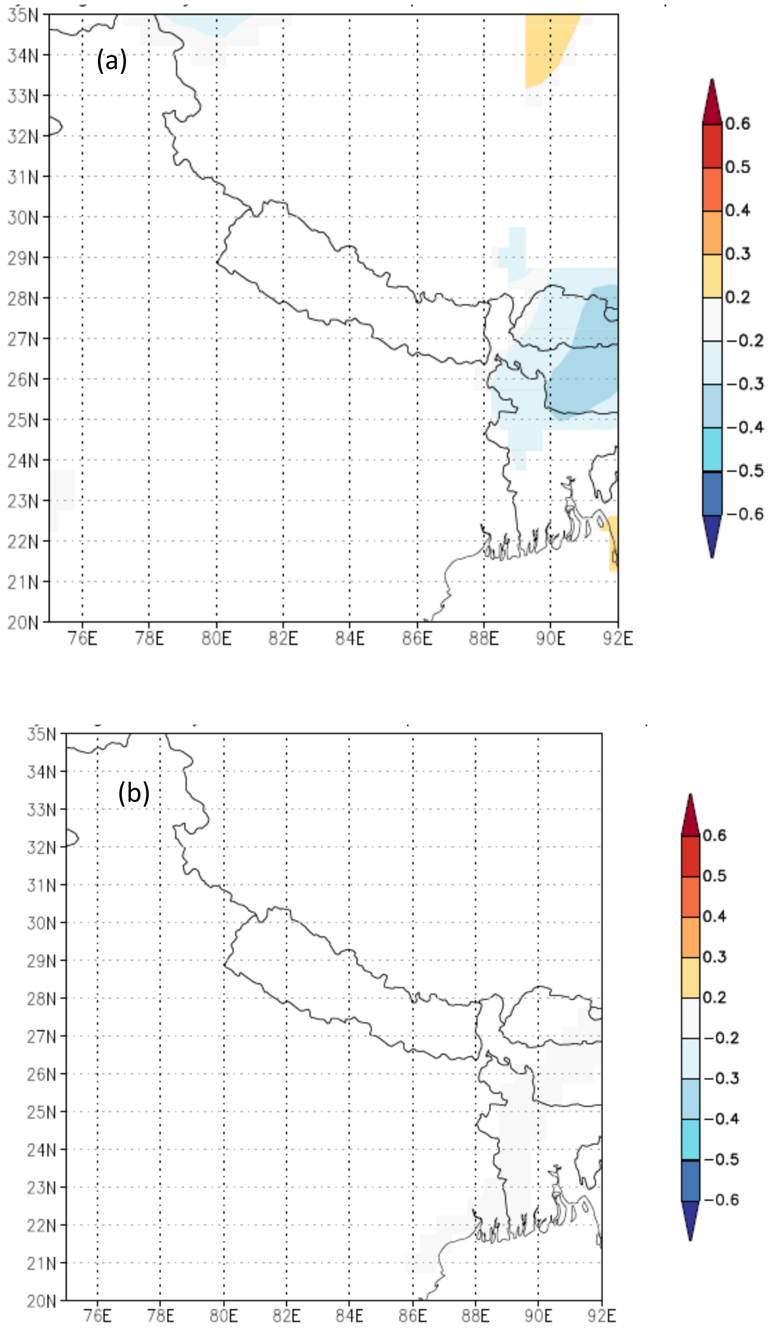


Figure 43: Spatial correlation ($p < 10\%$) between the observed (a) and reconstructed (b) MJJA average temperature in Manaslu Conservation Area with the CRU3.22 temperature data covering same time interval.

4.6.3. Climate reconstruction: western Nepal (Rara National Park)

From the growth-climate response analysis from RNP, it was found that climate reconstruction of March-June period is theoretically possible. Hence, the transfer function explained by Fritts (1976) was applied for the climate reconstruction of March–June months in the western Nepal. The transfer function was in the form:

$$T_{MAMJ} = a \text{ RW} + c$$

$$P_{MAMJ} = a \text{ RW} + c$$

Where, T_{MJJA} and P_{MAMJ} are the mean March-June temperature and precipitation, RW is the ring-width index, *a* and c are the regression coefficients. These models were subjected to the *F* test of significance using the entire climate records available 1957–2012 AD for precipitation and 1969-2012 AD for temperature. It was found that the temperature and precipitation transfer function were highly significant at 1%. The reconstruction was subjected for rigorous validation test using leave-one-out cross-validation test which passed the validation test with positive RE and CE value (Table 13), indicating robustness of the model.

Table 13: Validation statistics of the reconstruction model of the MAMJ total precipitation in Rara National Park area, Nepal Himalaya

Leave-one-out cross-validation statistics	
R	0.509
r2	0.259
Adjusted r2	0.245
F	18.88
RE	0.211
CE	0.114
Durbin-Watson test	1.613

Based on the ring width index chronology of the *A. spectabilis* from the RNP area, precipitation of the spring season (March to June) was reconstructed for the period of 1840-2013 AD (Fig. 44). This reconstruction captures 26% of the precipitation variability of the region. The reconstructed precipitation shows several moist and dry periods, rather than any persistent trend. Precipitation during 1855-1875, 1950-1970, and 1980s onward was low. Embedded into a persistent decreasing trend, several short moist periods can be seen. After the 1980s, the precipitation was continuously decreasing. The reconstructed precipitation captures the precipitation change in the north western part of the Nepal and some part of the western Indian Himalaya and

Tibetan plateau (Fig. 45). This also revealed that the region is more influenced by the westerly precipitation than the eastern summer monsoon.

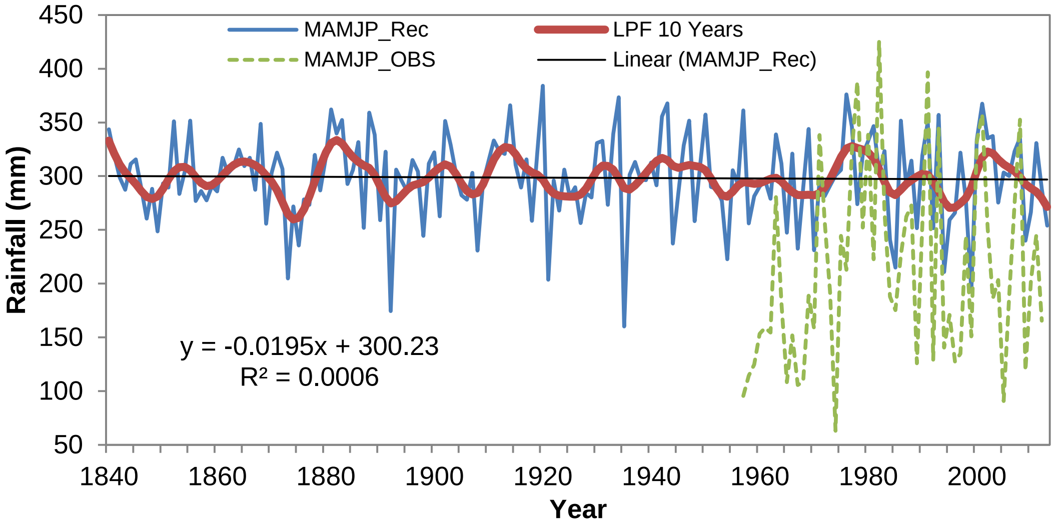


Figure 44: March to June precipitation (MAMJP) reconstruction in Rara National Park, Nepal Himalaya based on tree-ring width chronology of *Abies spectabilis*. The 10-year low pass filter (LPF) to the reconstruction and observed data are also shown.

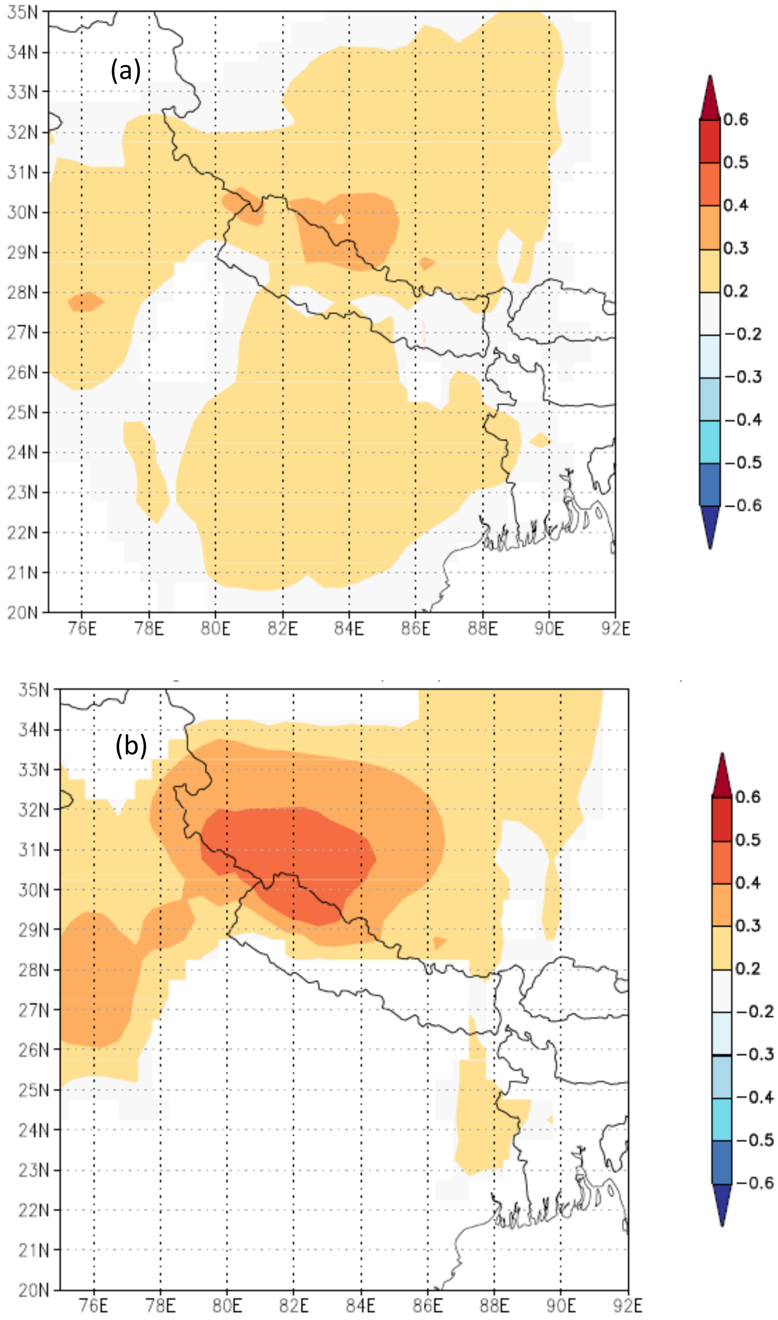


Figure 45: Spatial correlation ($p < 10\%$) between the observed (a) and reconstructed (b) MAMJ precipitations in Rara National Park, Nepal Himalaya with the CRU3.22 precipitation.

Relationship between the reconstructed precipitations with Sea Surface Temperature (SST) index of different region of the equatorial Pacific viz., NINO1.2, NINO3, NINO3.4 and NINO4 (Kaplan et al., 1998) and extended multivariate ENSO Index (MEI) (Wolter & Timlin, 2011) was carried out to test the teleconnection between the climate of the Himalayas with the various regional and global circulation models (Table 14).

Table 14: Relationship (Pearson's correlation) between the reconstructed MAMJ precipitation in Rara National Park Area, Nepal Himalaya with the different sea surface temperature index and various El-Nino indexes like SOI, NINO3, NINO3.4, NINO4, and NAO. The values in bold red color are significant at 95% or above confidence limit.

Month/seasons	SOI	NINO3	NINO4	NINO3.4	NAO	MEI
Jan	-0.131	0.128	0.141	0.133	-0.022	-0.02
Feb	-0.087	0.147	0.135	0.121	-0.025	-0.01
Mar	**-0.168**	**0.17**	0.141	0.131	0.07	0.00
Apr	-0.156	**0.186**	**0.199**	**0.173**	-0.001	0.05
May	-0.107	**0.205**	**0.204**	**0.17**	0.109	0.13
Jun	-0.068	**0.214**	0.141	**0.184**	-0.04	0.14
Jul	-0.09	**0.167**	0.101	0.141	-0.064	0.19
Aug	-0.174	0.152	0.083	0.133	0.032	0.23
Sep	-0.148	**0.179**	0.141	0.158	0.045	0.24
Oct	-0.133	0.16	0.132	0.136	-0.023	0.19
Nov	-0.026	0.143	0.108	0.126	**0.181**	0.16
Dec	-0.065	**0.176**	0.101	0.169	0.038	0.18
Jan-Apr	**-0.173**	0.165	0.163	0.145	0.007	
Feb-May	**-0.177**	**0.19**	**0.18**	0.156	0.061	
Mar-Jun	**-0.171**	**0.216**	**0.187**	**0.177**	0.068	
Apr-Jul	-0.138	**0.215**	**0.178**	**0.185**	-0.004	
May-Aug	-0.128	**0.197**	0.143	**0.17**	0.015	
Jun-Sep	-0.134	**0.185**	0.128	0.162	-0.009	
Jul-Oct	-0.156	**0.171**	0.125	0.148	-0.003	
Aug-Nov	-0.142	0.162	0.124	0.142	0.126	
Sep-Dec	-0.11	**0.167**	0.125	0.151	0.118	

The North Atlantic Oscillation (NAO) and El Nino-Southern Oscillation (ENSO) are the two leading modes of climate variability influencing climate over large parts of the Earth (Yadav, 2011a). This study revealed that precipitation of the western Himalayas is influenced by some common phenomenon like the North Atlantic Oscillation (NAO) and NINO3-SST index of El Nino-Southern Oscillation (ENSO), the leading modes of climate variability influencing climate over large parts of the Northern Hemisphere (Yadav, 2011a). There is positive relationship between the precipitation change in MAMJ in Nepal Himalayas and different Nino events, especially in the NINO3 region (Table 14). The NINO3 SST index is a measure of the amplitude and phase of ENSO, is defined as the monthly SST averaged over the eastern half of the tropical Pacific (5°S–5°N, 150–90°W (Kaplan et al., 1998). Similar response was observed in western Indian Himalaya (Yadav, 2011a). Yadav (2013) also indicated that the NAO is directly related with the MAMJ precipitation reconstruction over the corresponding months ($r = 0.18$, $p<0.05$), indicating that positive phase of NAO with the intensification of Azores High and deepening of the Icelandic Low strengthens the westerlies thus bringing more precipitation in the western Himalayan region (Yadav, 2013). Compared to western Nepal, the relationship was stronger in the northwestern Himalaya of India though there is temporal instability in the relationship (Yadav et al., 2009; Yadav, 2011a).

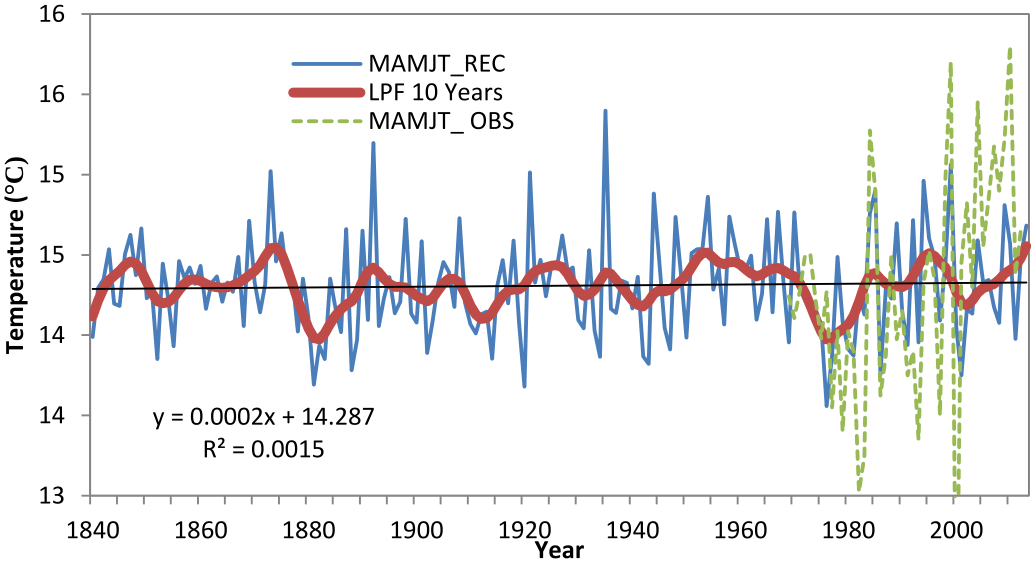


Figure 46: *Abies spectabilis* tree-ring width chronology based March to June temperature reconstruction from Rara National Park, Nepal Himalaya with 10 years low pass filter and observed data superimposed on graph.

Table 15: Validation statistics of the reconstruction model of the MAMJ average temperature of Rara National Park, Nepal Himalaya.

Leave-one-out cross-validation statistics	
r	0.481
r2	0.231
Adjusted r2	0.213
F	12.62
RE	0.160
CE	0.034
Durbin-Watson test	1.757

Based on the ring width index of the *Abies spectabilis* from RNP area, temperature of the spring and early summer months (March-June, MAMJ) for the period of 1840-2013 AD was reconstructed (Fig. 46). The reconstruction passed the validation test based on leave-one-out cross-validation test (Table 15). This reconstruction captures the 23% variability in the temperature in the region. The reconstructed temperature shows several warm and cool periods. The short cold episodes were observed around 1880s, 1910s while warm episodes were centered in 1870s, 1890s, and 1980s. The temperature in the region is constantly increasing after 1980s consistent with the station data. The reconstructed temperature captures the temperature change in the mid and far western Nepal, some part of western Himalaya of India (Fig. 47). Correlation analysis was performed between estimated average March–June (MAMJ) temperature with Sea Surface Temperature (SST) index of different region of the equatorial Pacific viz., NINO1.2, NINO3, NINO3.4 and NINO4 (Kaplan et al., 1998) and extended multivariate ENSO Index (MEI) (Wolter & Timlin, 2011) to test the teleconnection between the climate of the western Nepal Himalaya with the various regional and global circulation systems (Table 16). The estimated March–June temperatures had significant negative correlations with SSTs index and MEI for monsoon and post monsoons seasons (Table 16). These negative relationships suggest that warm spring season over the western Nepal Himalaya region are associated with cool SSTs in the following seasons and vice-versa. Similar observation between spring temperature reconstruction and SST are also noted in western Nepal (Thapa et al. 2014) and north western India (Yadav et al., 1997).

Table 16: Relationship (Pearson's correlation) between the reconstructed MAMJ temperature of Rara National Park, Nepal Himalaya with the different sea surface temperature index and various El-Nino indexes like SOI, NINO3, NINO3.4, NINO4, and NAO. The values in bold red color are significant at 95% or above confidence limit.

Month	SOI	NINO3	NINO4	NINO3.4	NAO	MEI
Jan	0.061	-0.079	-0.112	-0.085	0.081	-0.17
Feb	0.030	-0.108	-0.104	-0.081	0.022	-0.17
Mar	0.136	**-0.158**	-0.105	-0.111	-0.046	-0.20
Apr	0.101	-0.155	-0.150	-0.125	0.021	-0.21
May	0.122	-0.155	-0.127	-0.097	-0.122	**-0.38**
Jun	0.047	**-0.172**	-0.104	-0.133	0.051	**-0.44**
Jul	0.026	**-0.161**	-0.069	-0.116	0.045	**-0.36**
Aug	0.133	**-0.156**	-0.072	-0.129	-0.041	**-0.34**
Sep	0.097	**-0.167**	-0.115	-0.146	0.039	**-0.25**
Oct	0.067	-0.145	-0.122	-0.138	0.040	**-0.25**
Nov	-0.056	-0.129	-0.080	-0.118	-0.087	**-0.28**
Dec	0.005	**-0.164**	-0.065	-0.155	-0.054	**-0.28**

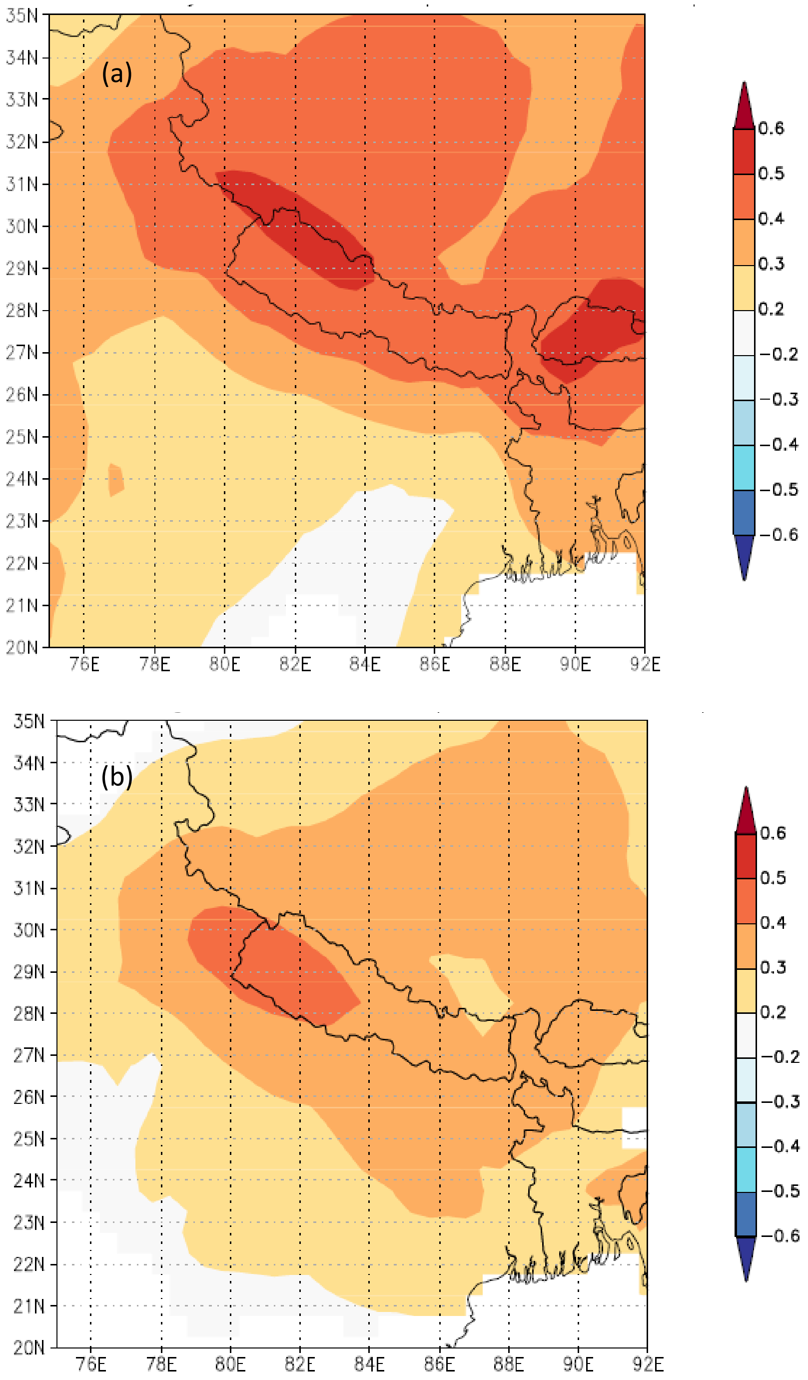


Figure 47: Spatial correlation ($p < 10\%$) between the observed (a) and reconstructed (b) MAMJ average temperature in Rara National Park, Nepal Himalaya with the CRU3.22 temperature.

The reconstructed MAMJ temperature shows several warm and cool episodes along with an insignificant warming trend. This reconstruction is compared with other temperature reconstructions from Nepal viz. February-June (Cook et al., 2003), March-September (Sano et al., 2005) and March-May (Thapa et al., 2014). Present reconstruction did not perfectly match with these other reconstructions; however, some common signals have been captured or shared. The recent warming trend is also observed in *Picea smithiana* tree ring based reconstruction of March-May temperature (Thapa et al., 2014) and *Abies spectabilis* ring width based reconstruction of March-September temperature in western Nepal Himalaya (Sano et al., 2005). However, all Nepal February-June temperature reconstruction using tree rings chronologies of multiple species has revealed a cooling trend in last decades of 20th century but October-February temperature reconstruction revealed a warming trend in recent decades (Cook et al., 2003). Some other cool and warm periods were also common with March-October west Nepal temperature reconstruction (Sano et al., 2005).

4.7 Limitation of the study

This study is limited in the treeline ecotone and focusing mainly on only two species i.e. *Abies spectabilis* and *Betula utilis*. Studies incorporating all treeline forming tree species within a plot or site including herbs and shrubs may give better idea for vegetation dynamics in response to climate and other environmental changes. Several biotic and abiotic factors affect treeline dynamics, however, this study focused mainly on the climatic factor of the treeline dynamics. Further studies incorporating role of competition between trees and shrubs, forest fire, soil nutrients and characteristics, grazing exclusion & transplantation experiment, masting in seed production, testing of growth or carbon limitation in the treeline formation are essential for better understanding of response of treeline and their dynamics with future climate change.

In present study, age of *B. utilis* is calculated based on regression model between age and diameter of the sample trees. This regression not necessarily captures the heterogeneity in growth of some tree species in natural environment. We had to pool together the site levels data for stronger regression in SNP. Hence, census sampling of tree cores will be more useful in age estimation of *B. utilis*.

Differential response is found in diffuse and abrupt treelines. In-depth studies are necessary why these types of treelines in Nepal Himalaya are formed and how they respond to environmental change. Due to financial constraints to stay in the field for long period, doing experiment in field and sampling in multiple aspects is not possible. Therefore, the impact of aspect within a site and area on the growth climate response could not be analyzed.

As this study is concentrated in the treeline region, ring width chronologies we developed cover short time span. For climate reconstruction, old trees can be found in mid distribution range of the species. Sampling in that area will be helpful to extend the length of chronologies, and improve quality and length of reconstructions.

CHAPTER 5

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusions

The present study provided an insight on contemporary treeline position with associated species composition, recruitment pattern and treeline dynamics, climatic response of growth and regeneration of Himalayan fir (*Abies spectabilis*) and Himalayan birch (*Betula utilis*) at the high elevation alpine treeline of the eastern, central and western parts of Nepal Himalaya. In addition to this, present study also reconstructed the climatic history of the central and western Nepal. The treeline position generally decreased from the eastern to the western parts of Nepal. Although regeneration patterns varied between the species and sites, increasing trends of stand densification as well as upward shifting of the studied treeline is evident in most of the sites. The treelines with diffuse form were more likely of shifting with climate change than in abrupt treelines. The treeline formed by *A. spectabilis* is more likely to shift upwards than that formed by *B. utilis*.

The growth-climate response and regeneration-climate response is species-specific and site dependent. Depending upon the study sites, the growth of the *A. spectabilis* was limited by temperature and or moisture stress. The growth of *B. utilis* in some sites was limited due to the moisture stress during spring season with the positive relation with precipitation and negative relation with the temperature of the same season, and some sites due to low or insufficient temperature during growing season. The climatic response of regeneration of *A. spectabilis* and *B. utilis* in the treelines was species-specific, site dependent and spatio-temporally varied. Both temperature and or precipitation limit the regeneration depending on the species and site condition.

Spatial and temporal variations in age structure and regeneration pattern of these two species and their species-specific response to climate indicated that the plant communities at the treeline ecotone in the Nepal Himalaya are sensitive to climate change and the studied treelines are changing. However, upward shifting is not a sole and unidirectional response to climate warming. Poor recent regeneration in upper reaches of many treeline plots indicates that along with favorable climate, site dependent abiotic factors, and age dependent species-specific competitive abilities with krummholz and dwarf scrub belts during the recruitment phase, and intensity of grazing will determine the future treeline dynamics in the region.

The meteorological data have shown an increasing mean annual temperature but a weakening precipitation in the study areas. The reconstructed average temperature of March-June months in western Nepal for the period of 1840-2013 AD by using ring width chronology of the *A. spectabilis* shows several warm and cool periods, along with insignificant positive trend. However, the temperature in the region is constantly and significantly increasing after 1980s consistent with the station data. Similarly, reconstructed March-June precipitation shows a slight negative trend though insignificant statistically, along with several moist and dry periods. The teleconnection analysis between the reconstructed temperature and precipitation with the different sea surface temperature index revealed a linkage with global circulation phenomenon.

5.2. Recommendations/future research prospects

From this study following points are put forwarded as recommendations for future studies.

As the information on basic research on growth dynamics of many tree species in Nepal Himalaya are missing.

1. Studies incorporating all tree species within a plot or site including shrubs at treeline will bring better idea for vegetation dynamics in response to climate change.
2. In present study, age of *Betula utilis* was calculated based on regression model between age and diameter of the sample trees. This regression not necessarily captures the heterogeneity in growth in natural environment. Hence, census sampling of tree cores will be more advantageous in age estimation of *B. utilis*.
3. Treeline shifting in the Himalaya is not a general trend. Differential response is found in diffuse and abrupt treelines. In-depth studies are necessary why this type of treeline forms and how they respond to environmental change.
4. Role of mountain aspects in the growth climate response can be analyzed incorporating the sampling in multiple aspects within a site.

5. Further studies incorporating soil nutrients and characteristics, effects of shrubs in the seedling survival, permafrost layer dynamics, fire dynamics, grazing exclusion and transplantation experiment, masting in seed production, testing of growth or carbon limitation in the treeline formation are essential for further enhancing our understanding on response of treeline and their dynamics with respect to future climate change.
6. Response studies covering the influence of elevation gradient, site heterogeneity and species association will give an insight to realistically isolate climatic influence and predict the vulnerabilities of species in different habitat due to climate change.
7. For climate reconstruction, old trees can be found in mid distribution range of the species. Sampling in that area will extend the length of a chronology and quality of chronology. Present study considered only the ringwidth parameter as a predictor variable for the climate reconstructions, studies incorporating other parameters like wood anatomical features of the rings, wood density and stable isotopes in the tree rings may increase the predictor variables and the robustness of the climate reconstruction using multiparameters.

CHAPTER 6

6. SUMMARY

6.1. Treeline position and associated species composition with size parameters in Nepal Himalaya

Treeline ecotone of the study areas were formed by *Abies spectabilis, Betula utilis, Juniperus recurva, Rhododendron campanulatum* and *Sorbus microphylla,* and with *Salix* sp in some sites.

The position of tree and species limit of the treeline forming *A. spectabilis* and *B. utilis* generally decrease from eastern to western part of Nepal Himalaya. In SNP (eastern Nepal), *A. spectabilis* species limit was at 4141 m asl and tree limit was found 4134 m asl and *B. utilis* tree and species limit 4132 m asl. In MCA (central Nepal), *A. spectabilis* treeline was found at 3907 m asl and the *B. utilis* treeline at 4003 m asl. In RNP (western Nepal), *A. spectabilis* limit was found at 3870 m asl and *B. utilis* treeline and species line was found at 3953 m asl.

The average *A. spectabilis* density (27 plants/ha) in Dole/Phortse of SNP was lower than that of *B. utilis* density (127 plants/ha). The average density of *A. spectabilis* in MCA was found 243 plants/ha and *B. utilis* was found 192 45 plants/ha. The average density of *A. spectabilis* and *B. utilis* in RNP was found 21 plants/ha and 971 plants/ ha, respectively.

The size class distribution of the studied species ranged from an inverse-J to uni or multimodal bell shaped indicating site- and species-specific regeneration pattern. Among the two species, *A. spectabilis* has better regeneration than that of *B. utilis*. Most of the size parameters were decreased with increasing elevation in the most of the sites.

Among the three sites highest DBH of *A. spectabilis* was found at RNP (104 cm) followed by MCA (66 cm) and SNP (56 cm). Similarly, the highest DBH of *B. utilis* was also found in RNP (96 cm) followed by SNP (76 cm) and MCA (46.5 cm). The highest age of treeline forming *A. spectabilis* was found at SNP (181 year) followed RNP (169 year) and MCA (160 year), while maximum age of *B. utilis* was found at RNP (340 year) followed by SNP (270 year) and MCA (198 year). There is a positive relationship between various size parameters of trees. Most of the size parameters were decreased with increasing elevation.

6.2. Climate, tree ring chronology and growth-climate response

Available climatic data (stations and CRU) analysis for the study area (SNP, MCA and RNP) revealed a consistent increase in the mean annual temperature; however, no specific pattern in the precipitation was found.

Based on the ring-width analysis six ring-width site chronologies, three each for *A. spectabilis* and *B. utilis*, were prepared. The site chronology of *A. spectabilis* at SNP extended to 1838-2012 AD, while that for *B. utilis* ranged 1831-2012 AD. For MCA, a 229 year long (1782-2010 AD) tree ring-width chronology of *A. spectabilis* was prepared. The site chronology of *A. spectabilis* from RNP extended to 1763-2013 AD while that for *B. utilis* ranges 1872 to 2013 AD. These ring width chronologies showed fluctuations in the growth rather than any consistent growth trend.

The radial growth of the *A. spectabilis* growing in the treelines of the SNP is mainly limited due to the low temperatures during summer (JJA) growing season with a significant positive relationship between growth and average monthly temperature of August ($p < 0.05$) and average temperature of summer season. The radial growth of the *A. spectabilis* at the treeline of Kalchuman lake area of MCA was limited by the low temperature with a positive correlation between the ring width chronology and monthly maximum temperature in most of the month and a negative relationship with minimum temperature. The growth climate response revealed that the growth *A. spectabilis* of the RNP area is mainly limited due to moisture stress during pre-monsoon/spring months and seasons with a significant ($p < 0.05$) positive relationship between the growth and precipitation in March, April and May months and spring season (MAM). A high temperature during spring and summer negatively affected the growth with a significant ($p < 0.05$) negative relationship with average monthly temperature of March, May and June and seasonal average of spring and summer season.

The correlation function analysis revealed that there was a significant positive relationship ($p < 0.05$) between the radial growth of the *B. utilis* from SNP and monthly precipitation of October previous year, March and May months of the current year, spring season (MAM) precipitation, while a significant negative relationship with temperature of same season. The radial growth of the *B. utilis* in MCA was limited due to both moisture and temperature limitations. There was a significant positive relationship ($p < 0.05$) between the growth and average temperature of previous year August month, average and minimum temperature of current year June, July, August and September months and summer season (JJAS), and precipitation of previous year October. There was a negative relationship ($p < 0.05$) with average temperature of previous year November, current year's March and April month and spring (MAM) season. The growth climate response revealed that the growth of *B. utilis* from the treeline of RNP area is mainly limited due to low precipitation during pre-monsoon months and insufficient temperature during summer. There was a significant ($p < 0.05$) positive relationship between the growth and precipitation in previous year July, current year February, March, and winter season (DJF). A high temperature during summer months and seasons positively favoured the growth with a significant ($p < 0.05$) positive relationship with average monthly temperature of June and July of the current year and average temperature during summer season (JJA).

6.3. Regeneration and treeline dynamics

In site level comparisons, the seedlings and saplings of *A. spectabilis* are higher than that of *B. utilis*. The relative proportions of tree, saplings and seedlings as well as seedling to sapling ratio revealed that there was poor regeneration of *B. utilis* as compared to that of *A. spectabilis*.

In most of the plots and sites, the size parameters (age, diameter and height) were decreasing with increasing elevation. However, there exists site and species-specific nature in regeneration dynamics. In some sites seedling and saplings are surviving and growing several meters higher than the tree individuals. The average rate of upward shifting of *A. spectabilis* in SNP was 0.93 m/yr and *B. utilis* was 0.42 m/yr with recent stable position in majority sites. The average upward movement of the upper distribution limit of *A. spectabilis* at MCA was 2.61 m/yr; however, the *B. utilis* is stable in recent several decades. The spatio-temporal distribution of individuals of the *A. spectabilis* and *B. utilis* from the Chuchemara peak area of RNP shows that *B. utilis* colonized the area first and followed by *A. spectabilis*. The position of *B. utilis* was higher than the position of *A. spectabilis* in all transects. The treeline ecotone of the area is stable for past 50 to 150 years depending upon the plots.

The relationship between the tree establishment and regeneration is species-specific as well as site dependent. The regeneration of *A. spectabilis* at SNP was positively favored by the high temperature in both winter and summer. Regeneration of the *A. spectabilis* in the MCA was favoured positively by the above-average monthly maximum temperature during most of the months and above-average precipitation during dry warm summer months. The regeneration climate relationship from RNP revealed that the regeneration in this area is more sensitive towards the precipitation as compared to temperature. There was a significant positive relationship between the regeneration of *A. spectabilis* and Jumla stations' precipitation of March, July and December months and significant negative relationship between monthly average temperature of the May and July months. Regeneration-climate relation of *B. utilis* is spatio-temporally differentiated and unstable. The relationship with most of the months was weak and insignificant statistically. There was negative relationship between the regeneration and climatic data in most sites.

6.4. Climate reconstruction

The mean May–August temperature for 229 year from 2010 AD extending back to 1782 AD was reconstructed from MCA region. The reconstructed May–August temperature shows several warm and cool periods. This also shows the slight warming at the end of 20th century.

Precipitation of the spring season (March-June) was reconstructed for the period of 1840-2013 AD by using *A. spectabilis* from the RNP area. The reconstructed precipitation shows several moist and dry periods, rather than significant persistent trend. Precipitation during 1855-1875, 1950-1970, and 1980s onward was low. In between long decreasing trend, several short moist periods was seen. The precipitation was continuously decreasing after 1980s.

Based on the ring width index of the *A. spectabilis* from RNP area, temperature of the spring and early summer months (March-June) for the period of 1840-2013 AD was reconstructed. The reconstructed temperature shows several warm and cool periods along with a slight positive trend. The short cold episodes were observed around 1880s, 1910s, while warm episodes were centered in 1870s, 1890s, and 1980s.

These temperature and precipitation reconstruction captures the signal of climate change in the western Nepal Himalaya and some part of western Indian Himalaya and Tibetan plateau. The reconstructed May-August average temperature from MCA region does not match with the temperature change in the broader area revealing local influence.

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ANNEXES

LIST OF PUBLICATIONS

Full Papers

1. Gaire, N.P., M. Koirala, D.R. Bhuju, M. Carrer (2016). Site- and species-specific treeline responses to climatic variability in eastern Nepal Himalaya, Dendrochronologia (In press), http://dx.doi.org/10.1016/j.dendro.2016.03.001
2. Gaire, N.P., P. Rana, M. Koirala, D. R. Bhuju, M. Carrer (2015). Study of treeline ecotone to assess long-term impact of environmental change in Mt. Everest region, Nepal Himalaya, FUUAST Journal of Biology, 5(1):1-11.
3. Gaire, N. P. (2014). Dendrochronology for environmental change study: evidences from Nepal, In U.R. Khadka (ed) Contemporary environmental issues and methods in Nepal, Published by CDES-TU, Kathmandu Nepal, pp. 71-80.
4. Gaire, N. P., M. Koirala, D. R. Bhuju, H. P. Borgaonkar (2014). Treeline dynamics with climate change at central Nepal Himalaya. Climate of the Past, 10: 1277–1290, www.clim-past.net/10/1277/2014/ doi: 10.5194/cp-10-1277-2014.
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6. Gaire, N.P., M. Koirala, D.R. Bhuju (2013). Dendrochronological Studies in Nepal: Current Status and Future Prospects, FUUAST Journal of Biology, 3(1):1-9.

Other supplementary publications

1. Speer, J.H. , Bräuning, A., Zhang, Q.B., Pourtahmasi, K., Gaire, N.P., Dawadi, B., Rana, P. Dhakal, Y.R., Acharya, R.H., Adhikari, D.L., Adhikari, S. Aryal, P.C. Bagale, D. Baniya, B., Bhandari, S., Dahal, N., Dahal, S., Ganbaatar, N., Giri, A., Gurung, D.B., Khandu, Y., Maharjan, B., Maharjan, R., Malik, R.A., Nath, C.D., Nepal, B., Ngoma, J., Pant, R., Pathak, M.L., Paudel, H., Sharma, B., Hossain, M. S., Soronzonbold, B., Swe, T., Thapa, I., & Tiwari, A. (2016). Pinus roxburghii stand dynamics at a heavily impacted site in Nepal: Research through an educational fieldweek. Dendrochronologia (2016), http://dx.doi.org/10.1016/j.dendro.2016.01.005
2. Feng Shi, Quansheng Ge, Bao Yang, Jianping Li, Fengmei Yang, Fredrik Charpentier Ljungqvist, Olga Solomina, Takeshi Nakatsuka, Ninglian Wang, Sen Zhao, Chenxi Xu, Keyan Fang, Masaki Sano, Guoqiang Chu, Zexin Fan, **Narayan P. Gaire**, Muhammad Usama Zafar (2015). A multi-proxy reconstruction of spatial and

temporal variations in Asian summer temperatures over the last millennium, Climatic Change, DOI 10.1007/s10584-015-1413-3.

3. Thapa, U. K., S.K. Shah, **N. P. Gaire**, D. R. Bhuju, (2014). Spring temperatures in the far-western Nepal Himalaya since A.D. 1640 reconstructed from Picea smithiana tree-ring widths, Climate Dynamics, doi: 10.1007/s00382-014-2457-1.
4. Thapa U. K., S.K. Shah, **N. P. Gaire**, D. R. Bhuju, A. Bhattacharyya, G.S Thagunna (2013). Influence of climate on the radial growth of *Abies pindrow* in western Nepal Himalaya, Banko Jankari, 23(2):14-19.
5. PAGES 2k Consortium (Moinuddin Ahmed, Kevin J. Anchukaitis, Asfawossen Asrat, Hemant P. Borgaonkar, Martina Braida, Brendan M. Buckley, Ulf Büntgen, Brian M. Chase, Duncan A. Christie, Edward R. Cook, Mark A. J. Curran, Henry F. Diaz, Jan Esper, Ze-Xin Fan, **Narayan P. Gaire**, Quansheng Ge, Joëlle Gergis, J Fidel González-Rouco, Hugues Goosse, Stefan W. Grab, Nicholas Graham, Rochelle Graham, Martin Grosjean, Sami T. Hanhijärvi, Darrell S. Kaufman, Thorsten Kiefer, Katsuhiko Kimura, Atte A. Korhola, Paul J. Krusic, Antonio Lara, Anne-Marie Lézine, Fredrik C. Ljungqvist, Andrew M. Lorrey, Jürg Luterbacher, Valérie Masson-Delmotte, Danny McCarroll, Joseph R. McConnell, Nicholas P. McKay, Mariano S. Morales, Andrew D. Moy, Robert Mulvaney, Ignacio A. Mundo, Takeshi Nakatsuka, David J. Nash, Raphael Neukom, Sharon E. Nicholson, Hans Oerter, Jonathan G. Palmer, Steven J. Phipps, Maria R. Prieto, Andres Rivera, Masaki Sano, Mirko Severi, Timothy M. Shanahan, Xuemei Shao, Feng Shi, Michael Sigl, Jason E. Smerdon, Olga N. Solomina, Eric J. Steig, Barbara Stenni, Meloth Thamban, Valerie Trouet, Chris S.M. Turney, Mohammed Umer, Tas van Ommen, Dirk Verschuren, Andre E. Viau, Ricardo Villalba, Bo M. Vinther, Lucien von Gunten, Sebastian Wagner, Eugene R. Wahl, Heinz Wanner, Johannes P. Werner, James W.C. White, Koh Yasue, Eduardo Zorita). (2013). Continental-scale temperature variability during the past two millennia, **Nature Geoscience**, 6: 339-346. http://www.nature.com/doifinder/10.1038/ngeo1797 .
6. Cook E. R., P. J. Krusic, K. J. Anchukaitis, B. M. Buckley, T. Nakatsuka, M. Sano, PAGES Asia2k Members (M. Ahmed, H. Borgaonkar, X. Chenxi, G. Chu, Z. Fan, **N P. Gaire**, Q. Ge, K. Kimura, J. J. Palmer, T. Papina, M. Schwikowski, X. Shao, F. Shi, O. Solomina, Z. Usama, C. Xu, K. Yasue, M. Zaiki, K. Zhao, and J. Zheng) (2013).Tree-ring reconstructed summer temperature anomalies for temperate East Asia

since 800 C.E. *Climate Dynamics.*Vol 41, Issue 11-12, pp 2957-2972. DOI 10.1007/s00382-012-1611-x (2012).

TRAININGS AND WORKSHOPS PARTICIPATION

1. Training on **Wood Anatomy and Stable Isotopes in Treerings (**10-23 January, 2016) organized at Department of Geography, Fredrick-Alexander University, Erlangen-Nurnberg, Germany.
2. Future Earth/IGBP Joint Early Career Workshop on **Designing Transdisciplinary Research for Sustainability Challenges: Co-Design and Co-Production Considerations for Future Earth Research** (11 – 12 December 2015), Quadrus Center, Stanford University, California, USA.
3. Training on **Analysis of Stable Istotope in Treerings** (March 21-29, 2015) from Research Institute for Human and Nature, Japan.
4. **Pre-conference Field-week Training on Dendrochronology** (4-8 March 2015) of the 4th International Asian Dendrochronological Conference organized Central department of Hydrology and meteorology and Asian Dendrochronological Association (ADA) at Kathmandu, Nepal (Participant/Assistant Tutor).
5. Training on **Scientific Writing and Publishing** (3-4 November, 2014) organized by National Institute of Environmental Health Sciences (NIH) USA and Progressive Sustainable Developments Nepal (PSD-Nepal) in Kathmandu.
6. Capacity strengthening workshop on the **Contemporary Environmental Issues and Methods in Nepal** (13-16 September, 2014) organized by Central Department of Environmental Science, Tribhuvan University at Kathmandu(Participant/Resource person).
7. Orientation on **BSc Third Year Curricula in Environmental** Science (21-22 August 2014) organized by Institute of Science and Technology, TU in Kathmandu.
8. Training on **Environmental Survey and GIS** (29 June to 4 July 2014) organized by Central Department of Environmental Science, Tribhuvan University at Kathmandu.
9. Training on **Reconstructing Climate Using Dendrochronological Tools** (3-7 February 2014) organized by Treering Society of Nepal at Kathmandu.
10. Computerized training in **Advanced GIS Processing using ArcGIS and Remote Sensing using IDRISI** (40 hours) organized by NAST (22nd January, 2014 to 6th February 2014) and provided by Bristol Training and Research Center.

11. **Workshop and Training on Metrology and Meteorology** (10 September 2013), organized by EvK2CNR and NAST at Khumaltar, Lalitpur, Nepal.
12. **The 3rd SCO National Academies Summer School: Methods for Geochronology and Isotope** (16 Jul. 2012 to 5 Aug. 2012), organized by Institute of Tibetan Plateau Research, Chinese Academy of Sciences (ITP, CAS), at Beijing, PR China.
13. **A Joint TPE Training and TiP Summer School** (Oct-30 to 14 Nov, 2011), Dhulikhel, Nepal, organized by Third Pole Environment, Beijing, China.
14. **Pre-conference Field-week Training on Dendrochronology** (15-19 August, 2011) of the 2nd International Asian Dendrochronological Conference organized jointly by Institute of Earth Environment, Chinese Academy of Sciences (IEECAS) and Asian Dendrochronological Association (ADA) at Xi'an, China.
15. Training Workshop on **Effective Management of Climate Knowledge** (3-4 August, 2011) organized by NAST, NCCKMC and CDKN at Khumaltar, Lalitpur.
16. Training Workshop on **Tree Growth and Climate Effects Modeling** (27 June -1 July, 2011) jointly organized by NAST, IOF- Pokhara, ComForM, DFRS-GoN, University of Copenhagen, CDES-TU and Tree Ring Society of Nepal at Khumaltar, Lalitpur, Nepal.

PARTICIPATION AND PRESENTATION IN CONFERENCES SEMINARS AND WORKSHOPS

1. AGU Fall Meeting 2015 (14-18 December, 2015) organized by American Geophysical Union at San Francisco, USA. [Poster]
2. 4th PAGES International Asia 2k Workshop (19-20, March, 2015) organized by PAGES Asia 2k Network at Research Institute for Humanity and Nature, Kyoto, Japan. [Oral]
3. 4th International Asian Dendrochronological Conference: Treering and Climate change (9-12 March, 2015) organized jointly by Central Department of Hydrology and meteorology, Tribhuvan University, Asian Dendrochronological Association (ADA) and Ministry of Forest and Soil Conservation, Nepal at Kathmandu, Nepal. [Oral/Poster]
4. Nepal Italy seminar on collaborative research (27-28 February, 2015), organized by Tribhuvan University in Lalitpur, Nepal.
5. International Conference on Climate Change Innovation and Resilience for Sustainable Livelihood (12-14 January 2015), organized by The Small Earth Nepal in collaboration with various organization, at Kathmandu, Nepal. [Oral]
6. Conference on Quaternary Climate Change: New Approaches and Emerging Challenges (15-15, December 2014), organized by Birbal Sahni Institute of Paleobotany, Lucknow, India. [Invited speaker]
7. 3rd International PAGES Asia 2k Workshop (26 – 27, May, 2014) organized by PAGES Asia 2k Network at Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing China. [Oral]
8. International Conference on Plants, People and Climate 2013(5-7 November, 2013) organized by Pakistan Council for Science and Technology and Treering lab, FUUAST at Islamabad, Pakistan. [Invited plenary speaker]
9. International Conference on Mountains and Climate Change (October 23-25, 2013), “High Summit”, Lecco, Italy organized by Ev-K2-CNR. [Poster}
10. International conference on Forests, People and Climate: Changing Paradigm (28-30 August, 2013, Pokhara Nepal) jointly organized by Institute of Forestry, Tribhuvan University, Department of Forest Research & Survey, Government of Nepal and Faculty of Science, University of Copenhagen [*Oral*].
11. PAGES 4th Open Science Meeting (13-16 Feb, 2013), Goa, India. [*Poster*]

12. PAGES 2nd Young Scientist Meeting (1-12 Feb, 2013), Goa, India. [*Poster*]
13. Sixth National Conference on Science and Technology (November 10-12, 2012), organized by Nepal Academy of Science and Technology at Kathmandu. [*Oral*]
14. International Conference on Climate Change: Opportunities and Challenges (9-11 May, 2012) organized by Pakistan Council for Science and Technology at Islamabad, Pakistan. *[Invited speaker*]
15. 2nd International Asia 2k workshop (9 – 11, January, 2012) organized by PAGES Asia 2k Network at Chiang Mai, Thailand. [*Oral*]
16. Workshop on Scope, Issues, and Challenges on Environmental Studies in Nepal (13 December, 2011), organized by Department of Environment Science of Patan Multiple Campus at Laitpur. [*Oral*]
17. The Third International Conference/Workshop on Dendrochronology and Plant Ecology (25-30 Nov 2011) organized by Federal Urdu University of Arts, Science, Technology at Karachi, Pakistan. [Invited speaker/*Resource person*]
18. 2nd International Asian Dendrochronological Conference (20-23 August, 2011) organized jointly by Institute of Earth Environment, Chinese Academy of Sciences (IEECAS), Asian Dendrochronological Association (ADA) The State Key Laboratory of Loess and Quaternary Geology (SKLLQG) and Xi'an Jiaotong University at Xi'an, China. [*Oral*]

PHOTOGRAPHS

Glimpses of fieldworks and labworks


Establishment of transect plot


Measurement of height of saplings

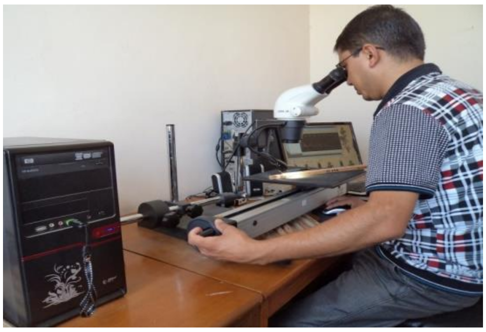

Recording presence of seedlings and saplings


Collection of tree core sample


Mounting of tree cores


Sanding and polishing of tree core samples


Tree-rings in samples after sanding and polishing


Measurement of ringwidth in the LINTAB system in Dendrolab

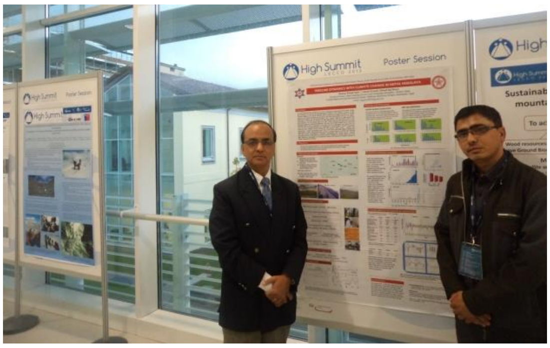
Participation and presentation in conferences and workshops

Presentation in AGU Fall Meeting 2015, December 2015, Sanfrancisco, USA

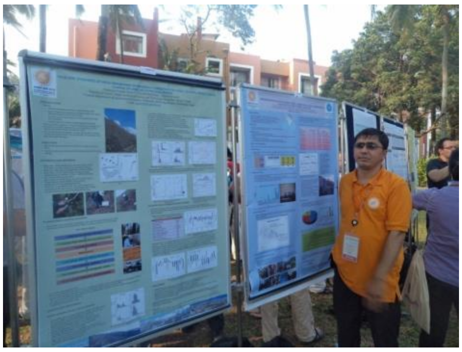
Participation and presentation in PAGES Asia 2k Workshop on Climate Reconstruction, May 2014, Beijing, China

Presentation in International Conference on Plants, People and Climate, November 2013, Islamabad, Pakistan

Presentation in Quarternery Climate Change, December 2014, Lucknow, India



Presentation in International Conference on Mountains and People, High Summit 2013, October 2013, Lecco, Italy



Presentation in PAGES 2nd Young Scientist Meeting and 4th Open Science Meeting, January 2013, Goa, India

Participation and presentation in the conferences and seminars

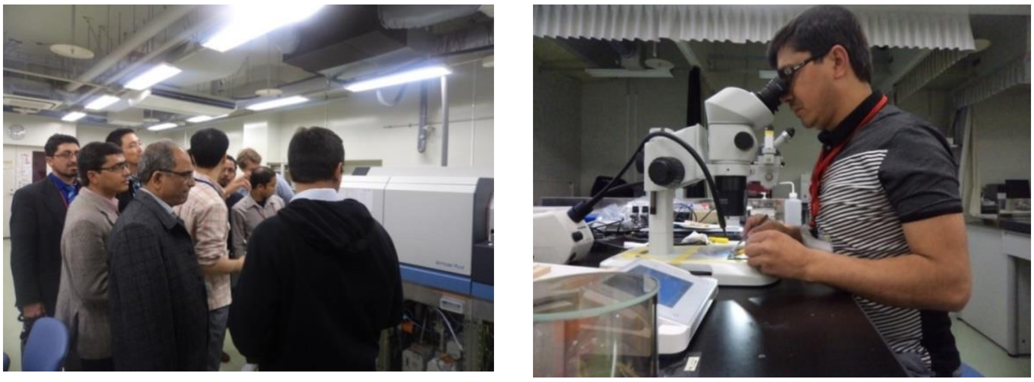
Fourth Asian Dendrochronology Conference, March 2015, Kathmandu, Nepal

PAGES Asia 2k 4th Workshop, March 2015, Kyoto, Japan

Quaternery Climate Change Conference, December 2014, Lucknow, India

Participation in trainings and workshops

Wood anatomy and stable isotope analysis training at Fredrich-Alexander Uuniversity, Erlangen-Nunberg, Germany, January 2016



Visits and isotope analysis training in Research Iinstitute for Humanity Nature, Kyoto, Japan

Future Earth/IGBP Joint Early Career Workshop, December 2015, Stanford University, California, USA

GAIRE ET AL (2013), *FUUAST J. BIOL.*, 3(1): 1-9

DENDROCHRONOLOGICAL STUDIES IN NEPAL: CURRENT STATUS AND FUTURE PROSPECTS

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Abstract

This study aims to know the current status of various aspects of tree ring (dendrochronological) studies in Nepal and assess its future prospects. The first tree ring research in the country was carried out in 1970s, after which a steady progress is seen till date with only 56 tree ring studies reported in published and unpublished research reports, thesis and journal articles. Studies have covered some 15 tree species in which the most favored tree for the study has been *Abies spectabilis* and the most widely used parameter for analysis has been the ring width. The longest chronology for Nepal was build from *Tsuga dumosa* with 1,141 years that extended from 856 AD to 1996 AD. On climatic reconstruction, three studies were found that covered temperature from 1546 AD to 1991 AD. Past studies have covered areas like dendroclimatology, dendroecology, dendroarchaeology and stable isotopes in dendrochronology. By geographic coverage, 22 districts out of 75 in the country have been covered, and they are mostly from high altitudes. Recent dendroecological studies have revealed an upward shift of *A. spectabilis* at treeline as well as differential regeneration pattern of treeline forming species in east, central and western Nepal of Himalaya. When analyzed by participation, 50% of the total studies up to now were carried out by Nepali researchers, 29% by foreign researchers and 21% in joint endeavors. For future, a potential of application tree ring study in wider aspects including dendrohydrology, dendroentomology, geomorphology and glaciology with large spatial coverage of the country is seen.

Introduction

Dendrochronology (word derived from Greek dendron, "tree limb"; khronos, "time"; and, -logia-study) is defined broadly to include all studies where the annual growth layers have been assigned to or are assumed to be associated with specific calendar years (Fritts, 1976; Speer, 2010). Dendrochronology or tree-ring dating is the scientific method of dating based on the analysis of patterns of tree-rings. Dendrochronology can date the time at which tree rings were formed, in many types of wood, to the exact calendar year. It is the interdisciplinary science with wider applications. It has several sub-discipline focused in particular area like dendroclimatology, dendroarchaeology, dendroecology, etc.

Dendrochronology is based on some basic principles and concepts like: The Uniformitarian Principle, Principle of Limiting Factor, Concept of Ecological Amplitude, Site selection, Sensitivity, Cross Dating, Repetition, Standardization, Modeling growth- environmental relationships, and Calibration & Verification (Fritts, 1976). Tree rings are an exceptionally valuable source of paleo-climatic information and tree ring data can be used to reconstruct the yearly variations in climate that occurred prior to the interval covered by direct climatic measurements. Tree rings can also be used to establish the year in which an event such as occurrence of an earthquake, landslide, volcanic eruption, or fire and even the date when a panel of wood cut, as long as the event involved the maiming or killing of a tree (Fritts, 1976). The climate phenomena seen through tree rings have spatial scales from a few hectares to a hemisphere, and temporal scales from the few hours of an ice-storm, through decades of drought, to centuries of changed global atmospheric circulation (Hughes, 2002). Tree rings are the most important and widely used sources of long-term proxy climatic data.

Dendrochronology is a young discipline in the realm of sciences with the first Laboratory of Tree-Ring Research established at the University of Arizona in 1937 (Fritts, 1976; Speer, 2010). A. E. Douglass, the founder of the Laboratory of Tree-Ring Research at the University of Arizona is taken as father of dendrochronology (Fritts, 1976). In spite of its recent modern history, the idea that tree produce annual rings had been suggested since time of Theophrastus in 322BC (Studhalter, 1956, cited in Speer, 2010). Dendrochronology is very popular discipline in present context. In the Hindu Kush Karakoram Himalayan region, the history of the subject especially for climate reconstruction is very young as compared to other region. Studies on tree rings in India in forestry aspects such as the evaluation of growth rates, wood productivity and quality, or rotation cycles have been recorded since long back (Gamble, 1902 cited Bhattarcharyya and Shah, 2009), but systematic tree-ring research based on accurate dating of long sequences of growth rings had only been started since the end of the 1980s (Bhattarcharyya and Shah, 2009). In Pakistan the field of dendrochronology seems to be started its step during 1980s (Ahmed, 1989). In case of Nepal collection of tree cores is started at the end of 1970s, however, institutional study is started much later.

The existence of natural microclimate gradients on mountains at high elevations offers one way in which a better understanding of species responses to small changes in climate can be obtained and enables potential plant responses to future climate changes to be evaluated (Liu *et al*., 2006). The highlands of south-central Asia possess a diversity of natural archives (e.g. lake sediments, loess, tree rings, ice cores, glacier fluctuations, geomorphologic features, and palaeobotanical fossils) from which long detailed palaeoclimatic records might be developed (Cook *et al*., 2003). Wide array of habitats representing major biomes of the world in graded climates in mountainous topography of Nepal and cultural diversity of the country provides a great potential in multidimensional tree ring research. This study tries to disclose the various aspects of so far conducted tree ring studies from Nepal including type of methodology used, temporal and spatial coverage of studies, studied species, chronology length, scope of study and research collaboration.

Materials and Methods

This paper is prepared by reviewing the published and unpublished literatures which deals with tree ring researches in Nepal. Literatures were searched by using some key words like tree ring, dendrochronology, dendroclimatology, dendroecology, dendroarchaeology in Nepal. In this study literature published (also conference proceeding, abstract, Thesis, projects) up to the end of August 2012 is incorporated. Similarly, for ongoing research, those studies which were carried out with close contact of NAST's dendrolab were also included.

Results and Discussion

Among the several proxy records tree-ring studies provides high-resolution climate. Based on several earlier work and many other recent publication it has been noted that there is a rapid progress in tree-ring analysis on its multifarious applications especially its potentiality on climatic reconstruction. In Nepal, a total 56 un/published researches or literatures based on tree-ring analysis has been found. Various aspects of tree ring studies covered in Nepal are analyzed in following sub headings.

Methodological aspect: In methodological aspect so far conducted studies have covered wider aspects. Most of the studies, almost all Nepali researchers, have used ring width parameter as a tool for past dendrochronological studies in Nepal. Some studies (Kobayashi *et al*., 2002; Sano *et al*., 2002, 2005; Bräuning, 2004) have used wood densitometry (X-ray densitometry) technique to calculate the density of early wood and late wood of each tree ring which have added the number of parameter that can be used in dendrochronological studies and also the quality of the research. Only two studies (Sano *et al*., 2010, 2012) were found which used stable isotope in tree ring for the past climate change study in Nepal. No one study was found using wood anatomical features for past environmental studies. These studies suggested that combination of wood densitometry and isotope analysis, besides ring width parameter, is best and appropriate approach for tree ring studies in Nepal (Bhattacharyya *et al*., 1992; Sano *et al*., 2005) because it not only improve the quality of research but also increase predictor variable in tree ring research.

Temporal aspect of study: Fig.1 presents temporal aspect of dendrochronological studies carried out in Nepal. Initially dendrochronological studies in Nepal was started by foreign researchers. According to the Bhattacharyya *et al.* (1992), earlier tree-ring collections in Nepal initiated in the late-1970s (1979-1980) by Rudolf Zuber who collected tree ring samples of diverse species and habitats. However, first tree ring related research from Nepal was published in 1990 by Suzuki. Bhattacharyya *et al.* (1992) extended Dendro study in Nepal by collecting large scale wood samples and described ten ring width based chronologies and reviewed the prospects for further dendroclimatic work in Nepal, they also pointed the good potentiality of some conifer tree species like: *Pinus wallichiana, Cupressus dumosa, Cedrus deodara*, *P. roxburghii*, *and Abies spectabilis* for dendroclimatic study. Later this work is further extended by Cook's team. Cook *et al*. (2003) used Zuber collected core samples as well Dr Burghardt Schmidt collected sample from living trees and archaeological wood in the dry inner valleys of north-central Nepal to develop master chronologies of various species. They carried out extensive and intensive sampling in Nepal and developed 32 tree ring chronologies using different tree species (Cook *et al*., 2003). Research publications on the Dendro study in Nepal are seemed to be increased slowly at beginning while faster in recent years (Fig.1). At 2002 the publications on tree ring studies from Nepal was increased and reached to six in which contribution of studies by Japanese researchers is crucial besides few Nepali researchers (Furuta *et al.,* 2002, Khanal and Rijal, 2002; Sano *et al.,* 2002a, b; Yasue *et al.,* 2002). Studies after 2010 increased rapidly mainly due to the contribution of Nepali researchers after the establishment of the first Dendro lab in Nepal Academy of Science and Technology in 2009. Increasing trend in number of studies and publication on tree ring is continue in 2012; at this period more than 10 tree ring researches in different parts of the country were active.

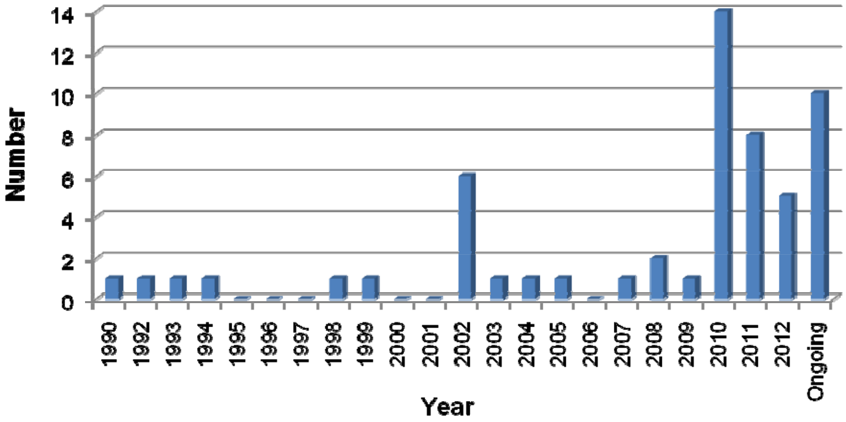

Fig.1. Number of dendrochronological studies by year of publications.

Spatial coverage of studies

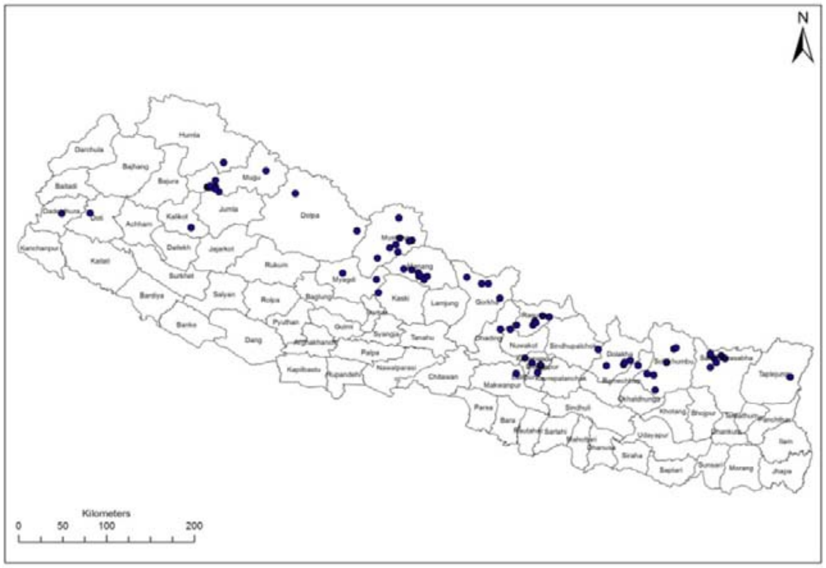

Fig. 2. Distribution of sampling sites for dendrochronological studies in Nepal.

Dendrochronological studies have been extended from far east to far west of Nepal Himalaya (Fig.2). So far these studies covered more than 22 districts of middle mountain to higher Himalaya of Nepal. Altitude of these studies were ranged from about 1000m to 4300 masl. Tree-ring studies carried out so far in the Nepal Himalaya region are mainly restricted to the lower temperate and sub alpine forests growing below treeline (egs. Suzuki, 1990; Bhattacharyya *et al*., 1992; Cook *et al*., 2003; Bräuning , 2004; Sano *et al.,* 2005, Chhetri and Thapa, 2010, Ghimire, 2012). Few tree ring studies are found from treeline of Nepal Himalaya (egs. Bhuju *et al*., 2010, Gaire *et al.,* 2011) and subtropical region (Regmi, 1998). But, no one study was conducted in Terai and Siwalik/Churiya area comprising tropical and subtropical region of the country, which is consistent with global trend in neglected tropical area. Many studies are concentrated on some pocket area or region in which Langtang region come in first from where more than 10 studies have been carried out. So there is a great discrepancy in the spatial coverage of the tree ring studies in Nepal.

Species coverage and chronology length: So far 15 tree species are used in Dendrochronological studies in Nepal. Wood sampling of following species like *Abies spectabilis, Acer sp, Alnus nepalensis, Betula utilis, Cedrus deodara, Juniperus indica, Juniperus recurva, Larix potanini, Picea smithiana, Pinus roxburghii, Pinus wallichiana, Rhododendron campanulatum, Sorbus sp, Tsuga dumosa, Ulmus wallichiana*, etc have been collected. However, tree ring chronologies can be established only for nine species namely *Abies spectabilis,* *Betula utilis, Cedrus Deodara, Juniperus Recurva, Picea smithiana, Pinus roxburghii, Pinus wallichiana, Tsuga dumosa, Ulmus wallichiana* (Suzuki, 1990; Bhattacharyya *et al*., 1992; Cook *et al*., 2003). Among these species, *Abies spectabilis* is most studied tree species which can be found in about 75% literatures followed by *Betula utilis* (22.9%), *Pinus wallichiana* (16.7%) and *Pinus roxburghii* (12.5%). Wide use of *Abies spectabilis* may be due to clear annual ring, easy for core sampling and distribution in wider areas. Most of these studied were confined to soft wood or conifer species, while few studies were conducted in broad leaved trees like *Betula, Rhododendron, Alnus*, etc. Therefore there is great prospect of multi-aspect tree ring studies in Nepal using various new tree species growing in diverse environment. No one studied shrub species of Nepal which may also an area of possibility in future.

Table 1. Length of longest ring width chronologies of selected tree species from Nepal.

Species	Chronology length	Duration(AD)	References
Abies spectabilis	603	1395-1997	Cook *et al*., 2003
Betula utilis	458	1552-2009	Dawadi *et al.,* 2012
Cedrus deodara	264	1714-1978	Bhattacharyya *et al*., 1992
Juniperus recurva	582	1717-1998	Cook *et al*., 2003
Picea smithiana	373	1628-2000	Furuta *et al*., 2002
Pinus roxburghii	297	1683-1979	Bhattacharyya *et al*., 1992
Pinus wallichiana	694	1303-1996	Cook *et al*., 2003
Tsuga dumosa	1141	856-1996	Cook *et al*., 2003
Ulmus wallichiana	432	1566-1997	Cook *et al*., 2003

While looking at the annual ring width chronologies length of different species, it varies from species to species (Table 1). Though different researchers developed varied length of chronologies, here, we only present the longest chronology length for available species. Longest chronology for Nepal was build for *Tsuga dumosa* which has the length of 1141years and extends from 856AD to 1996AD. For *Abies spectabilis* 603 years long (1395-1997AD), *Pinus wallichiana* 694 yrs (1303-1996AD) and *Juniperus recurva* 582 years (1717-1998) long chronologies have been built up. The length of these chronologies may be extended back by further research.

Scope of study: Dendrochronology is a versatile discipline with wider applications (Fritts, 1976; Speer, 2010). With time and discoveries of the new technology, the application of tree ring has been increased. There are a number of sub disciplines of dendrochronology having focused in particular areas of environment like Dendroclimatology, Dendroecology, Dendroentomology, Dendroseismology, Dendrogeomorphology, Dendrohydrology, Dendroglaciology, Stable isotopes in dendrochronology, Wood anatomy in dendrochronology, Dendroarchaeology, and many more.

The major sub discipline of dendrochronology is Dendroclimatology which involves the reconstruction of past climatic variations of particular area. Most of the tree ring researches in Nepal are carried out with the aim of reconstructions of past climatic variations using tree rings, however, only few studies have succeeded to reconstruct past climate (Cook *et al.,* 2003; Sano *et al.,* 2005, 2012). Most of the research studies were confined to the response function analysis or tree growth–climate relationship analysis (egs. Suzuki, 1990; Bhattacharyya *et al*., 1992; Bräuning, 2004; Chhetri and Thapa, 2010; Tenca and Carrer, 2010; Dawadi *et al*., 2012). The main reasons of limitation in response function analysis is the lack of good quality climatic data with sufficient temporal coverage. The first published climatic reconstruction using tree ring data from Nepal on international journal was by Cook *et al.* (2003). They reconstructed past temperature of two seasons: February–June (1546–1991) and October–February (1605–1991) (Fig. 3). Each reconstruction indicates the occurrence of unusually cold temperatures in 1815–22, which coincides with the eruption of Tambora in Indonesia. After adjustment of probable missing multi-centennial temperature variance to each reconstruction, the resulting 'adjusted' reconstructions strongly reflect patterns of temperature variability associated with Little Ice Age cooling and warming into the 20th century, with the October–February season exhibiting the strongest increase in temperature over the past ~400 years. Only the October–February season shows any evidence for late- 20th century warming, whereas February–June temperatures have actually cooled since 1960 (Cook *et al*., 2003). Later, Sano *et al.* (2005) reconstructed the climate of western Nepal for the past 249 years by using relationship between climate and ring width & wood density of *Abies spectabilis*; result shows 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 (Fig.3). Recently a ∂^{18}O tree-ring chronology by Sano *et al.* (2012) has shown increasing aridity over the past 223 years in the Nepal Himalaya.

Dendroecology is an important sub discipline of dendrochronology. In this category studies related to impact of climate variability on stand dynamics and treeline dynamics as well as different aspect of forest management like fire frequency, pest infestations, annual increment of trees, etc, can be studied. Some studies related to this field were also conducted in Nepal. Most of them were focused at treeline (eg. Gaire, 2008; Dhakal, 2009; Ansari, 2010; Suwal, 2010, Bhuju *et al.,* 2010; Bista, 2011; Gaire *et al.,* 2011; Ojha, 2012). These studies have also focused on regeneration; some studies found differential regeneration and growth rate in treeline and timberline of Khumbu region (Bhuju *et al.* 2010) and some found different regeneration above and below treeline (Suwal, 2010; Bhuju *et al.,* 2010). Various studies revealed the consistent upward shifting of *Abies spectabilis* with a range of 1.56 to 3.4m per year in different region of the Nepal (Ansari, 2010; Suwal, 2010; Gaire and Bhuju, 2010). Future of dendrochronology is dendroecology because of practical implication of the knowledge derived from the tree-ring studies in various issues like climate change adaptation and forest or ecosystem management.

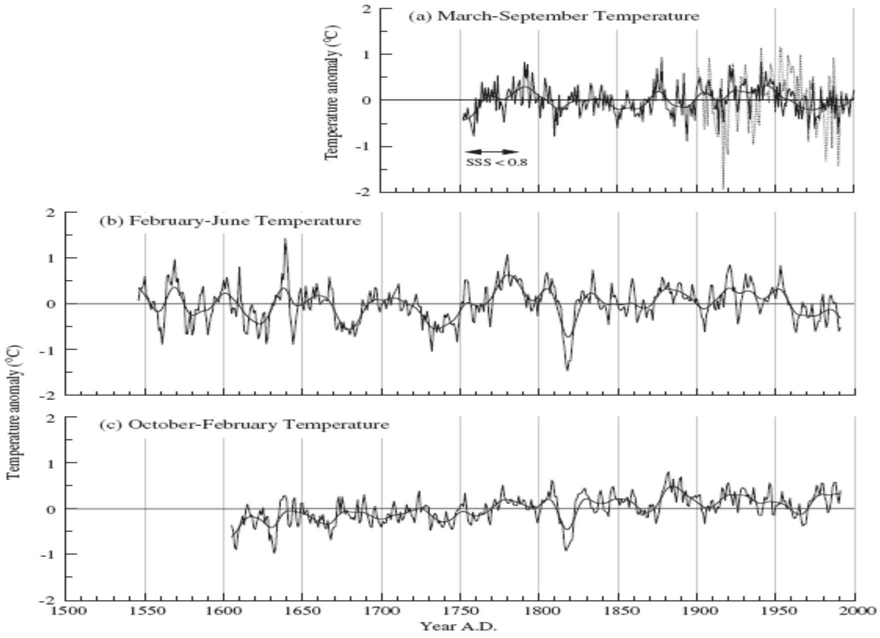

Fig.3. Reconstructed mean temperatures in Nepal, as deviations from the long-term means: (a) March–September with observed data (dotted line) (in Sano *et al.* 2005) (b) February–June and (c) October–February (in Cook *et al.* 2003).

Dendroarchaeology involves in the study of past cultures, civilizations as well as past climate by using tree ring from the archaeological sites (Fritts, 1976). This kind of studies was carried out in Nepal, mainly in the initiative of German scientists like: Dr. Burghardt Schidimit, Dr. Achim Brauning, Thomas wazny etc and Nepali researcher like Kuber Malla, during 1980s (Schmidt, 1992-93; Gutschow, 1994; Schmidt *et al.,* 1999). They have carried out extensive sampling of tree cores from archaeological excavations, old houses, monasteries and castles of high altitude region of the country like Mustang, Dolpa and Khumbu. From the study of tree ring of pine wood sample used in the monastery of Muktinath, Schidimit (1992-93) found that the woods used in the construction of the monastery (the youngest tree ring before being chopped down) was felled in 1906 and a specimen from the foundations of the kings palace in Dzarkot was found to be felled in 1512. Schmidt *et al.* (1999) established a master chronology for Nepal covering the time-span between AD 1324 to 1997 which can provide important information about the history and dynamics of the local settlements, local architecture, castles and monasteries along the old famous trade route between Tibet and India. Their result indicated the wider prospects of the dendroarchaeological studies in Nepal. Bhuju and Gaire (2010) studied the old pine stand of Kathmandu valley (Sallaghari Bhaktpur, Singhdurbar, Thapathali) to find the plantation history of these location and they found about 150 years old trees.

Stable isotopes used in dendrochronology (Stable isotopes in trees) i.e. different stable isotopes trapped in the tree rings can provide valuable information of the past climate or environmental change. Studies of this isotope analysis in trees rings are very limited in Nepal and only two publications by Sano *et al.* (2010, 2012) was found on this aspect. Sano *et al.* (2010) developed a 50-year tree-ring d^{18}O chronology of *Abies spectabilis* growing close to the treeline (3850masl) in the western region of Nepal Himalaya. From the response- function analysis with ambient climatic records they found that tree-ring δ^{18}O is primarily governed by rain fall during the monsoon season (June–September). Extreme dry years identified in instrumental weather data are also detected in the d^{18}O chronology. Tree-ring d^{18}O is much more sensitive to rainfall fluctuations than other tree-ring parameters such as width and density typically used in dendroclimatology. El Nino and ENSO phenomenon can also be studied by using this technique. A tree-ring δ^{18}O chronology of *Abies spectabilis* from the Nepal Himalaya revealed increasing aridity over the past 223 years extended from ad 1778 to 2000 (Sano *et al*., 2012). Though this technique gives more in-depth knowledge, due to lack of instrument in Nepal, development of this field will depend on the collaborations with foreign researchers.

Looking at the climate growth response, different researchers found different response at local level, however, they got common signal in their chronologies for certain pointer year. From study around Lake Rara, and performing a multiple regression analysis between ring widths and seasonal precipitation, Suzuki (1990) found that rain from May to August primarily affected the tree growth and that from September to December in the previous year secondarily. Ring width of birch from Dolpo Himalayas was highly correlated with summer temperature of the summer prior to growth, whereas ring width of fir was strongly correlated with temperature during the winter before the growing season as revealed by Brauning (2004). A study of *Abies spectabilis* from Humla, Sano *et al.* (2005) found that the ring width was correlated negatively with March–May (pre-monsoon) temperature and positively with March–May precipitation, while the minimum density was correlated positively with March–July temperature and negatively with March–May precipitation. These results indicate that the ring width and minimum density are primarily controlled by the pre-monsoon temperature and precipitation which is consistent to Suzuki (1990), while the latewood density by the late monsoon temperature (Sano *et al.* 2005).

Though wood anatomy act as an indicator of environmental factors, studies on Wood anatomy in dendrochronology was not carried out from Nepal. No study was conducted in Dendroseismology, Dendrogeomorphology, Dendroentomology, Dendrohydrology and Dendroglaciology in Nepal, though these fields also have huge potential in Nepal.

Research collaboration: Looking at the literature on the basis of nationality of the researchers, 50% of the studies were carried out by Nepali researchers followed by 29% by foreign researchers (Fig. 4). Only 21% studies have been carried out by collaborating each other. Among the non native researchers, contribution of American, Japanese, German and Indian researchers to foster the tree ring research in Nepal is high. In independent study by Nepali researchers, thesis studies contributed mainly.

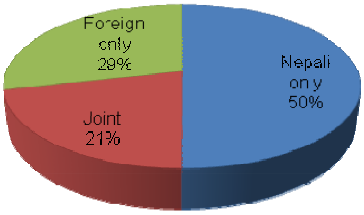

Fig.4. Tree ring research by the nationality of the researchers.

Looking at the temporal aspect of research collaboration, in the beginning, involvement of the Nepali in tree ring research was mainly as tourist guide or porter of foreign research expedition team. Only few Nepali have been involved in researchers' team. Looking at the authorship of the publications clearly shows this. After 2005, mainly after 2008, the contribution by Nepali researchers was found higher than that of non native researchers which was just opposite direction at before, which shows increased concern and interest of Nepali researchers on this field. Research collaboration is increased in the recent years (Fig. 5), however, which is still unsatisfactory. But, looking at those researches which are in progress, the collaboration is high as large numbers of the ongoing researches are carried out by the Nepali students studying in the foreign universities.

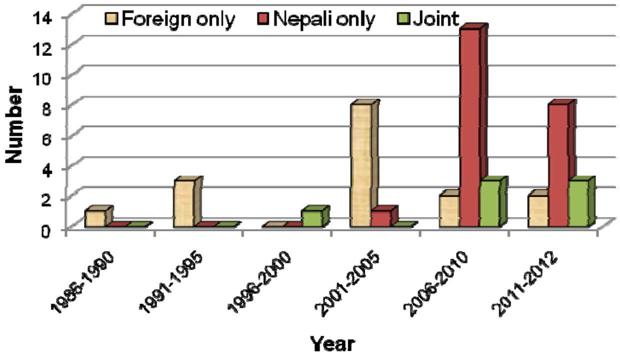

Fig.5. Research collaboration with time.

Prospects and challenges of future tree ring studies in Nepal: Mountainous country representing the major biome of the world in small geographical area, Nepal has ample opportunities for the multitude aspects of dendrochronological research. Existence of diverse forests and vegetation ranging from tropical forest to temperate forest and subalpine meadows, large number of rivers and glaciers, changing land use pattern may provide good platform for diverse research in the context of climate change, its mitigation as well as adaptation on it. It provides opportunities to work not only in the dendroclimatological aspect but it also has opportunities to link tree ring data to the cultural and land use change.

There are some of challenges of tree ring research in Nepal.

- Further expansion of dendrochronological studies in tropics as well as in new thematic areas like pollution or dendrochemistry, dendroentomology, etc.
- Expansion of the temporal and spatial replications of tree rings for the study of past environmental changes.
- Study of abrupt events (earthquakes, landslides, fires, climatic extremes) that have large impacts on society.
- Better understanding of vulnerabilities of humans to climate change.
- So far conducted dendro studies from Nepal covers dendroclimatology, dendroarchaeology, and dendroecology and isotope analysis, however, native researchers are engaged mostly on dendroecology and just response-function analysis. The challenge is how to strengthen the professional capabilities of the Nepali researchers to cover other aspects.
- Increment of investment of the government and private organizations in the field of research and development, particularly in the science and technology. Collaboration with and support from various organizations is very crucial.

Conclusion

This study reviews and summaries the result of tree-ring studies carried out (up to August 2012) from Nepal. A total of 56 studies (published and unpublished) were reported from Nepal, among them, 50% were carried out by Nepali researchers, 29% by foreign researchers and 21% studies were carried out in joint endeavors. Studies have covered more than 15 tree species and revealed several species like *Abies spectabilis, Betula utilis, Cedrus deodara, Juniperus indica, Juniperus recurva, Picea smithiana, Pinus roxburghii, Pinus wallichiana, Tsuga dumosa, Ulmus wallichiana*, which were promising for dendrochronological studies in Nepal. Longest chronology from Nepal was build using Tsuga dumosa which was 1141years long and extended from 856AD to 1996AD. Only three climatic reconstructions (temperature) studies were published in international journal covering different time period of seasons: February–June (1546–1991), October–February (1605–1991) and March–September temperature (1752-2000). The scope of dendroclimatology, dendroecology, dendroarchaeology and stable isotopes is carried out in 22 districts of the country. Large spatial coverage of country is still not explored. Therefore Dendrochronological studies should be extended in other areas of the country.

Acknowledgements

First author would like to express his gratitude to NAST for PhD fellowship. We are thankful to Mr. Madan Krishna Suwal for valuable suggestions in improving the manuscript and plotting the figures. We thank Prof. Dr. Moinuddin Ahmed and reviewer for their constructive comments in the manuscript.

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Clim. Past, 10, 1277–1290, 2014
www.clim-past.net/10/1277/2014/
doi:10.5194/cp-10-1277-2014
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Treeline dynamics with climate change at the central Nepal Himalaya

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Received: 7 August 2013 – Published in Clim. Past Discuss.: 28 October 2013
Revised: 22 April 2014 – Accepted: 15 May 2014 – Published: 4 July 2014

Abstract. Treeline shifting in tandem with climate change has widely been reported from various parts of the world. In Nepal, several impacts of climate change on the physical environment have been observed, but study on the biological impacts is lacking. This dendrochronological study was carried out at the treeline in the high mountain slope of Kalchuman Lake (3750–4003 m a.s.l.) area of Manaslu Conservation Area in the central Nepal Himalaya to explore the impact of climate change on the treeline dynamic. Two belt transect plots (size: 20 m wide, > 250 m long) were laid which included treeline as well as tree species limit. Ecological mapping of all individuals of dominant trees *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 years) compared to *A. spectabilis* (max. age 160 years). *A. spectabilis* contained an overwhelmingly high population (89 %) of younger plants (< 50 years) indicating its high recruitment rate. Population age structure along the elevation gradient revealed an upward shifting of *A. spectabilis* at the rate of 2.61 m year^{-1} since AD 1850. The upper distribution limit of *B. utilis* was found to be stagnant in the past few decades. An increment in plant density as well as upward shifting in the studied treeline ecotones was observed. The temporal growth of *A. spectabilis* was correlated negatively with the monthly mean and minimum temperature of June to September of the current and previous year. The regeneration of *A. spectabilis*, on the other hand, was positively correlated with August precipitation and monthly maximum temperature of the month of the current year. The growth and regeneration of *A. spectabilis* was more sensitive to maximum and minimum temperature rather than average temperature. The growth of the *B. utilis* was mainly limited by moisture stress during the pre-monsoon season. As these two species presented species-specific responses to climate change with differential pattern in regeneration condition, much wider differences are anticipated in their population status as climate continues to change throughout the century.

1 Introduction

During the past 100 years the global average surface temperature has increased by 0.74 °C ± 0.2 °C, and it is projected to rise by 1.4–5.8 °C by AD 2100 (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 biophysical 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; Kirdyanov 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 °C±0.8 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; Kirdyanov et al., 2012). Many dendroecological studies have documented that trees at the treeline often respond to climatic warming with an increase in recruitment or tree density as well as upward advances in the treeline position (Bradley and Jones, 1993; Camarero and Gutiérrez, 2004; Danby and Hik, 2007; Kullman, 2002, 2007; Batllori and Gutiérrez, 2008; Kullman and Öberg, 2009; Leonelli et al., 2011; Kirdyanov et al., 2012). A meta-analysis of a global data set, including 166 sites for which treeline dynamics had been recorded since AD 1900, 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 about our knowledge on the relationships of Hindu Kush–Karakoram–Himalaya (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 the 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 the 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 the Nepal Himalaya is reflected by shrinking permafrost areas (Fukui et al., 2007) and 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 several promising species for dendrochronological study, including *Abies spectabilis* and *Betula utilis* (Bhattacharyya et al., 1992; Cook et al., 2003; Sano et al., 2005; Dawadi et al., 2013), 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 the Nepal Himalaya (Bhuju 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 treeline, and (iii) analyse 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 describe 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 (MCA, area: 1663 km^2), a high mountain protected site in the central Nepal Himalaya, established in AD 1998. MCA has a diverse natural resource base with sparse human population and is relatively inaccessible. The area includes nine bioclimatic zones ranging from the lower subtropics to the nival zone with only marginal infrastructure, such as roads. It is the least explored protected area of the country. Local people depend on agriculture, animal husbandry and utilization of natural resources for their sustenance. Buddhism has positively contributed in protecting the forest and biodiversity (Chhetri, 2009).

The study site is a mountain slope adjacent to Kalchuman Lake situated at 3690 m above mean sea level (a.m.s.l.). With human settlements located not more than 2500 m a.m.s.l., the study site is little disturbed anthropogenically. There is a dense forest in between the settlement and study sites. Soil is rich in humus, dark in colour, and its depth 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 anthopogon* 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).

The climate of the study area is monsoon dominated. The mean annual rainfall over the past 30 years (1980–2009) at nearby meteorological station at Chame was 967 mm (SD = 280). The monthly average temperature was found to be highest in July and lowest in November (Fig. 1a). The highest recorded temperatures were 23.4 °C during June 1998, the lowest −4.5 °C during January of 1999 and 2000. Over the past 30 years, the station experienced a decreasing trend in rainfall by 3.9 mm year^{-1} ($n = 30$, $R^2 = 0.014$, $p < 0.52$) (Fig. 1b) and an increasing trend in mean annual temperature by 0.017 °C year^{-1} (Fig. 1c). In this station monthly mean minimum temperature was decreasing while monthly mean maximum temperature was increasing significantly (Supplementary Fig. S1). Similarly, mean annual rainfall at Larke, Gorkha, was 1252 mm (SD = 535). In Larke, during the past 30 years (1980–2009) there was a significant ($n = 30$, $R^2 = 0.26$, $p < 0.003$) decreasing trend of rainfall by 28 mm year^{-1} (Fig. 1b). 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 year^{-1} between 1987 and 2009.

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. 2). T1 was above the continuous forest, while T2 was situated above the middle part of the lake. It was also assumed that the lake might hinder the dispersal of seedlings in the area. Individual plants were categorized and enumerated into three height classes: trees (> 2 m), saplings (0.5–2 m) and seedlings (< 0.5 m), following 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 years (max. 4 years) in saplings and 1.27 years 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*.

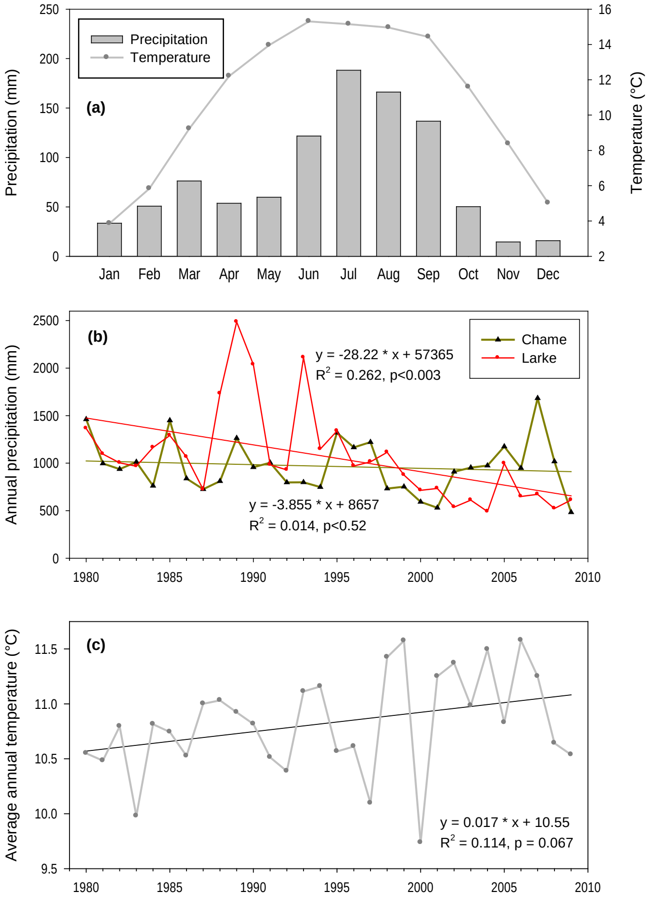

Figure 1. Climatic trend in the local stations: mean monthly (1980–2009) precipitation and temperature at Chame, Manang station **(a)**; annual trend of precipitation at Larke, Gorkha and Chame **(b)**, and trend of mean annual temperature at Chame **(c)**.

2.3 Tree core and cut-stump collection and analysis

Tree cores were collected using the increment borer (Haglöf, 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 the plots. A total of 249 cores and cut-stump samples (172 *A. spectabilis* and 77 *B. utilis*) were collected (Supplementary Table S1). Collected core and cut-stump samples

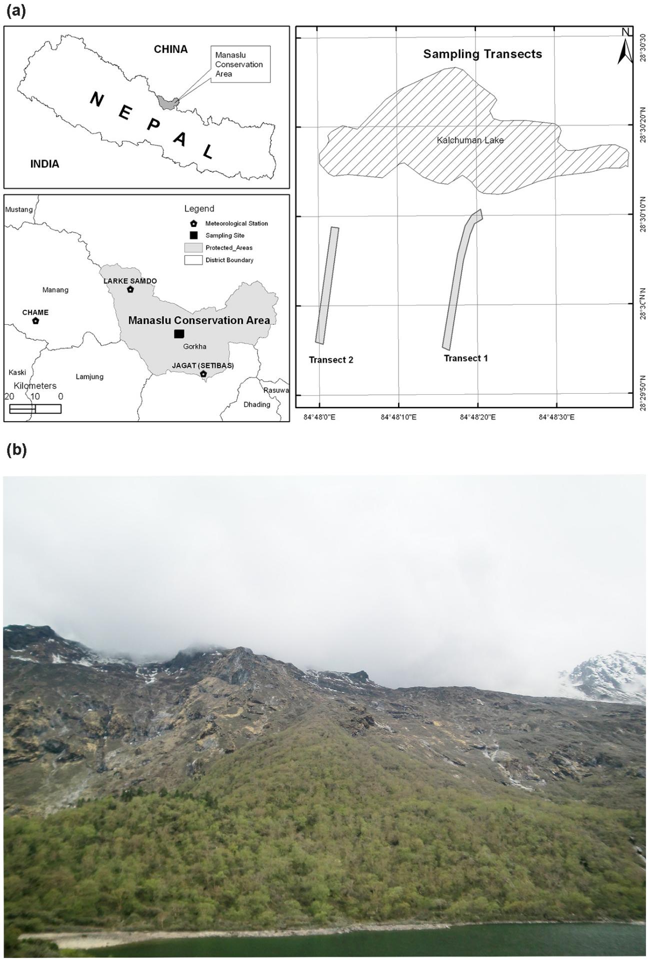

Figure 2. Location map of the study area showing the position of the study plots and local meteorological stations **(a)**, and a photo of the study site showing treeline, species limit and some portion of Kalchuman Lake **(b)**.

were taken to the Dendro-lab of the 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 (100–1000 grits size) until optimal surface resolution allowed 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$^{\mathrm{TM}}$ 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 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 modelling to remove any autocorrelation effects (Cook, 1987). Finally, three chronologies – namely 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. Temporal changes in the mean radial growth were assessed by doing regime shift (significant changes in mean radial growth) analysis (Rodionov, 2004). Regime shift was detected based on a statistical test whereby data are processed in time sequence and the hypothesis of a regime shift or discontinuity is tested for each new observation (Rodionov, 2004, 2006). We set the cutoff parameter at 10 years in order to detect changes in mean radial growth driven by high-frequency events and used a 95 % level of significance.

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 centre 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 centre (Camarero and Gutiérrez, 2004; Speer, 2010). For *B. utilis* cores from representative sample trees covering different diameter at breast height (DBH) classes were collected. Based on the ages of 39 *Betula* trees, a regression analysis model between DBH and age was established (Fig. 3), 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 tree individuals. The treeline dynamics was analysed by density 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 year^{-1}) was calculated by dividing the change in species limit elevation (position) by the time elapsed.

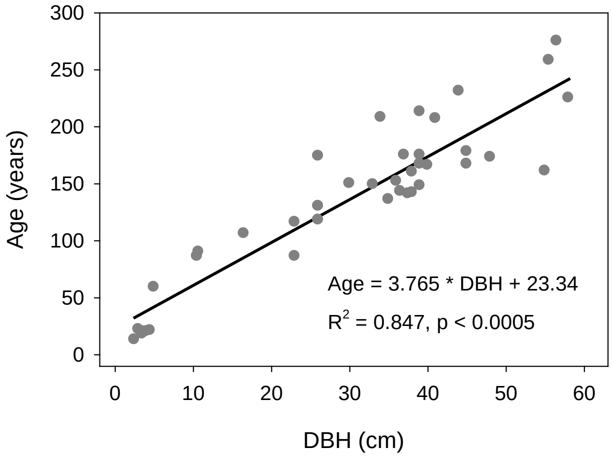

Figure 3. Diameter at breast height (DBH) versus age of *Betula utilis* from the Kalchuman Lake area, Manaslu Conservation Area.

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. 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 analysed the influence of temperature and precipitation since June 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 climate variables, i.e. monthly average (T_{mean}), maximum (T_{max}) and minimum (T_{min}) temperature and total monthly precipitation. Similarly, influence of seasonal climate on radial growth was also assessed for four seasons – namely winter (December–February, DJF), pre-monsoon (March–May, MAM), monsoon (June–September, JJAS) and post-monsoon (October–November, ON). In addition to this, influence of annual average temperature and total precipitation was also calculated. One of the major difficulties in undertaking dendroclimatic research in Nepal relates to the paucity of long meteorological records for statistically calibrating the tree rings because most of the weather stations in Nepal were only established after 1960 for precipitation and 1970 for temperature (Bhattacharyya et al., 1992; Cook et al., 2003). Available climatic data (1980–2009) of the nearest stations at Chame (28°33′ N, 84°14′ E and 2680 m a.s.l.) of Manang and Larke Samdo (28°40′ N, 84°37′ E and 3650 m a.s.l.) of Gorkha were used (Fig. 2). Missing values were replaced by average value of the same month's data.

To investigate the relationship between regeneration and climate change, recruitment or age data were summed across 5-year intervals as the finest resolution to take into account uncertainties in age estimates and compared with monthly climate records compiled into 5-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, maximum and minimum temperatures, and total precipitation) from Chame, Jagat 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 the 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 in T2 (Supplementary Table S2). The maximum age of *A. spectabilis* and *B. utilis* was higher in T1 than in T2. *A. spectabilis* tree density ranged from 50 to 280 trees ha^{-1}. 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 cm and 35–40 cm DBH class (Supplementary Fig. S2). 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 presents a unimodal bell shape, indicating poor regeneration in 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 (Supplementary Fig. S3).

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 (Supplementary Fig. S3 and Fig. 4). The age distribution of *A. spectabilis* indicated that the species was established in the early 1850s in T1 (Fig. 4a) and in the 1950s in T2 (Fig. 4b). The population of *A. spectabilis* was dominated by young individuals comprising 89 % of the population below 50 years age. The recruitment of *A. spectabilis* was slow in the 1850s, accelerating after 1950, and again after 1980. This could be related to increased temperature in the area. The recruitment of *B. utilis* started from the 1820s in T1, then reached T2 in the 1840s (Fig. 4a, b). The proportion of young population of *B. utilis* was low (13 % of the population $<$ 50 years old) as compared to middle-aged trees (42 % being 50–100 years old) and older ones (45 % over 100 years 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 the 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 the 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. 4a, 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 indicating upward migration (Fig. 4c). Matured trees and young seedlings were mostly dominant at lower elevation indicating stand densification as well. 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 the 1810s and 1820s and at 3990 m during the 1890s (Fig. 4a). The *A. spectabilis* on the other hand made a treeline community 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 m year^{-1} (1.56–3.66 m year^{-1}). The upward shifting of *A. spectabilis* was more pronounced in T2 with migration rate of 3.66 m year^{-1}, while it was 1.56 m year^{-1} in T1.

The densities of saplings and seedlings of *A. spectabilis* (Supplementary Table S3) indicated that its regeneration was higher in T1 than in T2 and also higher than that of *B. utilis* in both transects. As there was a presence of a large number of saplings and seedlings of *A. spectabilis* in the site but no seedlings of *B. utilis*, it is anticipated that the structure and composition of this treeline community will change in the future.

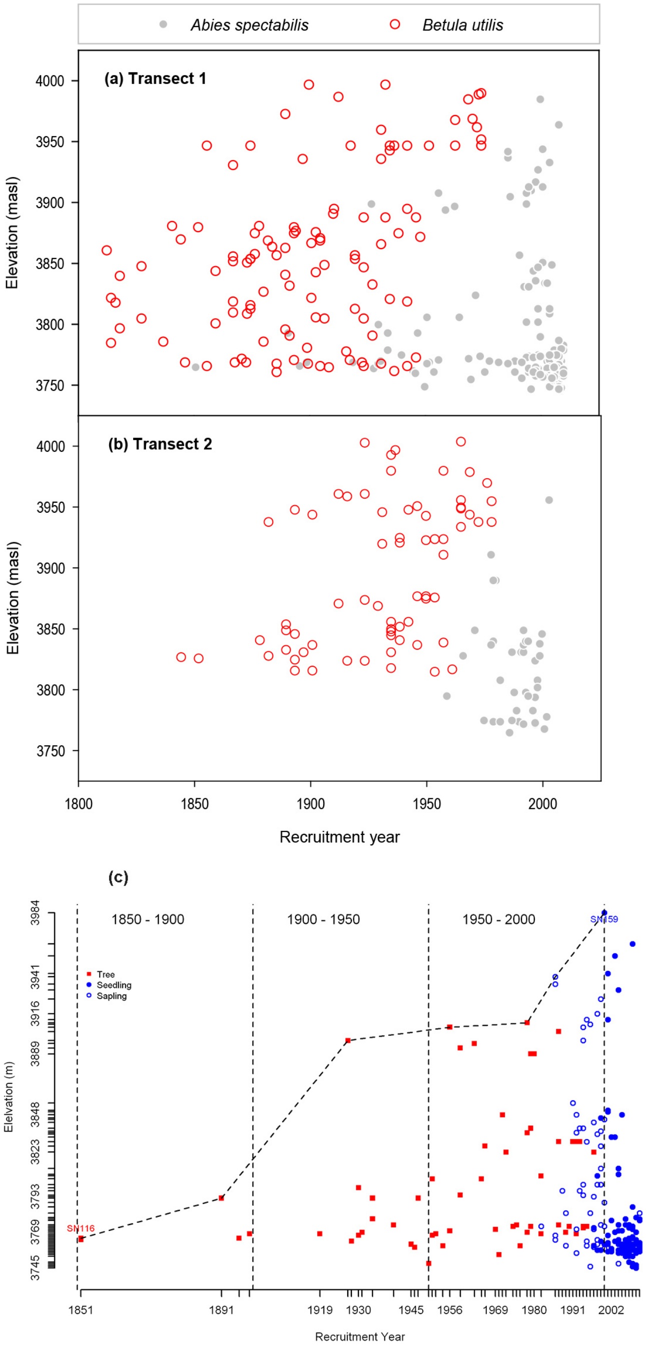

Figure 4. (a, b) Spatial and temporal variation in the recruitment of tree species in T1 and T2. **(c)** Temporal upward shifting of *Abies spectabilis* along an elevation gradient in the study site.

3.3 Tree-ring chronology

A 229-year-long (AD 1782–2010) 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 fluctuated 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. Results of the regime shift analysis suggest that there have been constant changes in mean radial growth which are dominated by short periods of above-average radial growth. Two major periods with low radial growth were 36 years starting in 1854 and 63 years starting in 1940. The period centred on 1905 is one of the shortest with below-average radial growth. In the recent period (after 2000) the radial growth is increased. Several statistics that were calculated for the time span of AD 1782–2010 and for the period of overlap (AD 1920–2005) of all tree-ring series indicated a high dendrochronological potential (Supplementary Table S4). The

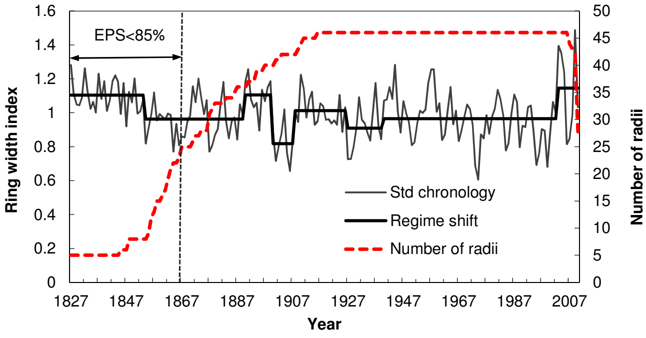

Figure 5. Tree-ring standard chronology of *Abies spectabilis* from the Kalchuman Lake area of Manaslu, central Nepal.

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 %.

3.4 Response of tree growth and regeneration to climate change

The radial growth of the *Abies spectabilis* at the studied treeline was limited by the low temperature with a positive correlation between the ring width chronology and monthly maximum temperature in most of the month and a negative relationship with minimum temperature (Fig. 6a). The radial growth in *A. spectabilis* correlated negatively with the mean and minimum monthly temperature of June–September ($r > -0.45$, $P < 0.01$) months of the current year (Fig. 6a). However, above-average monthly mean and minimum temperature in the previous year growing period (i.e. June–September) influence negatively the current year growth. Looking at the influence of seasonal climate on the growth, effect of monsoon season (JJAS) temperature on the growth was stronger than individual counterpart months with a significant negative correlation with seasonal mean ($r = -0.58$, $P < 0.01$) and minimum ($r = -0.66$, $P < 0.01$) temperature.

Though weak, radial growth was negatively correlated with monthly precipitation of most months of the current year (Fig. 6a). The relationship between ring width and precipitation of February of the current year was slightly negative ($r = -0.38$, $P < 0.05$). The precipitation during the previous year June correlated positively ($r = 0.45$, $P < 0.05$) with current year growth. The correlation between the radial growth and seasonal sum of precipitation was weak and not significant statistically.

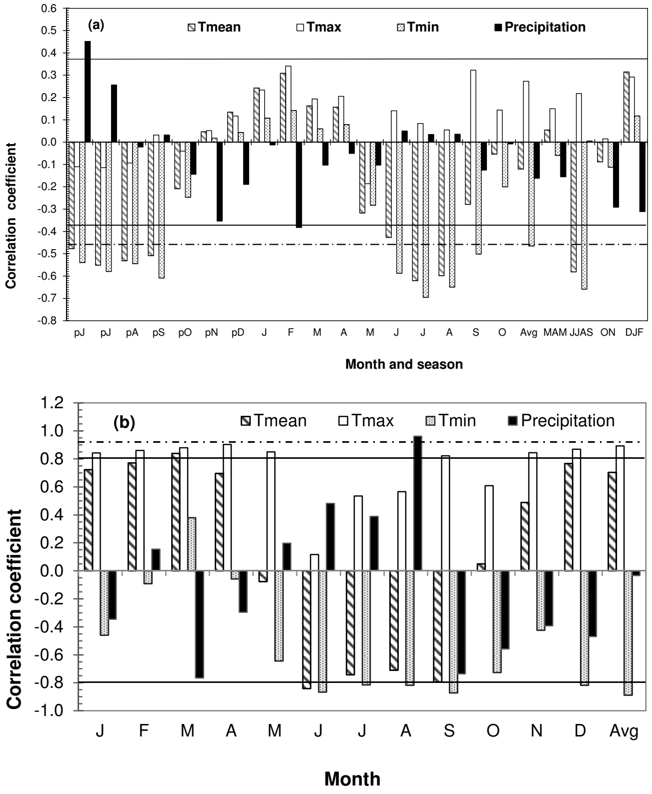

Figure 6. Relationship between the *Abies spectabilis*' radial growth with climate data (monthly mean, maximum, minimum, seasonal average temperature, and monthly and seasonal sum of precipitation) **(a)**, and relationship between regeneration *A. spectabilis* with monthly climate **(b)**; the black horizontal line indicates a significant correlation at the 95 % confidence limit for a two-tailed test and dashed horizontal line indicates a significant correlation at the 99 % confidence limit for a two-tailed test. **(a)** shows the response of radial growth to the monthly climate of June in the previous year to October of the current year as well as seasonal averages. pJ–pD signify June–December of the previous year; MAM, JJAS, ON and DJF are the mean temperature and the sum of precipitation of March–May, June–September, October–November and previous year December to the current year February, respectively. For climatic influence on the regeneration of the *A. spectabilis* a climatic window of 12 months of current years as well as annual average of temperature or annual sum of precipitation are used.

Regeneration of the *A. spectabilis* was favoured positively by the above-average monthly maximum temperature during most of the months and above-average precipitation during dry warm summer months (Fig. 6b). The relationship between regeneration and monthly maximum temperature of the most of the months of the current year was positive and statistically significant ($r > 0.8$, $P < 0.05$) while the relationship was negative but significant with the monthly minimum temperature of June–September of the current year ($r > -0.7$, $P < 0.05$) (Fig. 6b). The relation between regeneration and precipitation in August ($r = 0.96$, $P < 0.01$) was positive and statistically significant (Fig. 6b).

It is also evident from Fig. 6a and b that the growth and regeneration of *A. spectabilis* is more sensitive to minimum or maximum temperature rather than average temperature because correlation with these is more positive or negative than average.

4 Discussion

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 (Körner, 1998; Miehe et al., 2007).

In Nepal, the position of the treeline varies between the eastern, central and western region (Schickhoff, 2005). Regardless of the plots, 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; Bhuju et al., 2010; Liang et al., 2014). 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). Bhuju 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 Hindu Kush–Karakoram–Himalaya (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 our study, the structural parameters of the studied species not only varied between the plots but also between the species. Compared to T1, the smaller maximum DBH and younger age of both the *A. spectabilis* and *B. utilis* in T2 indicated some influence of the Kalchuman Lake in the seed dispersal in the T2 from downside seed source. The DBH class distribution of *A. spectabilis* shows a bimodal distribution in 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* indicated poor regeneration during recent years. The age distribution was an inverse-J-shaped to multimodal bell-shaped with intra and inter-species differences. Such kind of differences in the age and DBH class distribution of *A. spectabilis* and *B. utilis* have been observed in the other treeline ecotones of Nepal (Shrestha et al., 2007; Bhuju et al., 2010; Suwal, 2010; Gaire et al., 2011), indicating site- and species-specific regeneration condition in the Nepal Himalaya. Similarly at the *A. spectabilis* treeline near the Everest region on the Tibetan side, Lv and Zhang (2012) observed a multimodal age distribution with peaks during 1840–1860 and in recent years. The differential spatio-temporal regeneration pattern reflected in the multimodal size (age and/or DBH) class distributions were also observed in various treeline sites of different mountains: for example *Picea schrenkiana* in central Tianshan mountains, NW China (Wang et al., 2006), *Juniperus przewalskii* in the Qilian Mountains, NE Tibetan Plateau (Gou et al., 2012), *Pinus uncinata* in the Pyrenees Mountains, NE Spain (Camarero and Gutiérrez, 2007; Batllori and Gutiérrez, 2008), *Picea glauca* in SW Yukon, Canada (Danby and Hik, 2007), *Larix gmelinii* in the Putorana Mountains, northern Siberia (Kirdyanov et al., 2012), *Picea glauca*, *Picea mariana* and *Larix laricina*, *Abies lasiocarpa* near Churchill, Manitoba, Canada (Mamet and Kershaw, 2012).

Recruitment, critical determinant 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). The recruitment of *A. spectabilis* was high during the 1940–1950s and after the 1980s which might have been facilitated by the warm winter 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 in the treeline in the Himalaya and other mountains (e.g. Gaire et al., 2011; Batllori and Gutiérrez, 2008; 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 AD 1760–1960 in the treeline of the 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 the Tibetan mountains. Batllori and Gutiérrez (2008) also observed past and recent synchronous recruitment trends of *Pinus uncinata* with climate change at the treelines in the Iberian eastern range of the Pyrenees.

The regeneration at the treeline can be sporadic or episodic (Cuevas, 2002; Lv and Zhang, 2012). Patchy spatial distribution of *A. spectabilis*, with gaps in some diameter and age classes observed in the present study, indicates episodic regeneration. The dominance of multimodal age distributions also observed in other alpine or forest–tundra ecotone studies suggested that recruitment in treeline forest ecosystems is episodic or sporadic rather than gradual (Szeicz and MacDonald, 1995; Cuevas, 2002; Batllori and Gutiérrez, 2008; Lv and Zhang, 2012). The spatial distribution of *B. utilis* was more regular compared to *A. spectabilis*. In this study, establishment of *B. utilis* in recent decades has been very poor as compared to previous decades. A similar trend has been reported from other treeline sites (e.g. Bhuju et al., 2010). 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 the 1880s and 1940s. Similarly, the regeneration of *B. utilis* before the arrival of *A. spectabilis* was high. The maximum age of *B. utilis* was higher than *Rhododendron 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 understory tree *R. campanulatum* and was later invaded by *A. spectabilis* trees.

Seedling establishment is an important factor dictating the altitudinal limits of treeline species (Hughes et al., 2009). Evidently, treeline rise depends on seeds produced at the local treeline rather than propagulae from more distant sources at lower elevations (Kullman, 2007). 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 and young seedlings of *A. spectabilis* and matured *Betula* were mostly dominant in the lower elevation. However, some seedlings of *A. spectabilis*, probably due to global warming, have been thriving at much higher elevation than tree individuals. This study indicated both stand densification and upward migration as recorded in many other areas (Camarero and Gutiérrez, 2004; Danby and Hik, 2007; Gehrig-Fasel et al., 2007; Kullman, 2007; Vittoz et al., 2008; Batllori and Gutiérrez, 2008; Kullman and Öberg, 2009; Kirdyanov et al., 2012).

Consistent with the observed trend in the other treelines (Kullman, 2001, 2002; Wang et al., 2006; Kullman and Öberg, 2009; Gou et al., 2012), spatio-temporal age distribution showed that there was regeneration as well as upward migration of the *B. utilis* until the end of the 1960s though the exact rate is not calculated. The peak in the tree establishment in the past corresponds to the warm episode in both winter and summer reconstructed temperature in the country (Cook et al., 2003). However, we observed a stagnant upper distribution limit or treeline of *B. utilis* in the recent decades along with poor regeneration in spite of temperature warming in the area.

Average upward shifting of the upper distribution limit of *A. spectabilis* at the treeline ecotone was about 2.61 m year^{-1} with some local variation in the area. This upward migration trend of *A. spectabilis* is consistent with the upward migration (34 m per decade) of *A. spectabilis* in the treeline of the Samagaun region of the MCA (Suwal, 2010), and of *Pinus wallichiana* (19 and 14 m per decade on south- and north-facing slope) in the western Himalayas (Dubey et al., 2003). Several other studies have reported treeline shifting in different regions of the world (e.g. Camarero and Gutiérrez, 2004; Danby and Hik, 2007; Gehrig-Fasel et al., 2007; Harsch et al., 2009; Kullman 2001, 2002; Kullman and Öberg, 2009; Chauchard et al., 2010; Leonelli et al., 2011; Mamet and Kershaw, 2012; Kirdyanov et al., 2012). 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 of 70–90 m on average with maximum up-shifts of about 200 m since around AD 1915. Danby and Hik (2007) found an increased tree density as well as an advancement of Spruce (*Picea glauca*) treeline elevation by 65–85 m on south-facing slopes in southwest Yukon, Canada during the early to mid-20th century. Similarly, Kirdyanov et al. (2012) observed an upslope shift of the *Larix gmelinii* treeline position by approximately 30–50 m in altitude in the Putorana Mountains, northern Siberia during the last century. 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 years.

4.2 Climatic factors affecting tree growth and regeneration dynamics

Growth of a tree is associated with several abiotic factors including climate (Fritts, 1976). The radial growth of *A. spectabilis* fluctuated over time with changing climate and we did not observe constant increment or decrement in the growth. However, a few studies have reported enhanced radial growth of the western Himalayan conifer during recent years (e.g. Borgaonkar et al., 2011).

The radial growth of *A. spectabilis* in the treeline is more responsive to temperature change. Tree growth was positively correlated with temperature (T_{mean}, T_{max} and T_{min}) from October of the previous year to April of the current year which indicates that temperature before the growing season has a main influence on the radial growth during the subsequent growing period. High winter temperature may induce early melting of snow with the easy availability of melt water for growth in the growing season. Studies also have reported that monthly and seasonal winter temperatures are more limiting than growing-season temperatures to annual radial growth in many upper treeline sites with a positive relationship with winter temperature (Bräuning, 2004; Pederson et al., 2004; Borgaonkar et al., 2011). Bräuning (2004) found a strong positive relationship between the *A. spectabilis* ring width chronology and temperature from November of the previous year to January of the current year in western Nepal. Borgaonkar et al. (2011) found a strong positive relationship between the mean annual and winter (DJF) temperatures of the concurrent year and growth of western Himalayan conifers. The negative relationship, observed in the present study, with the pre-monsoon (MAM) and monsoon season (JJAS) temperature points towards some threshold temperature or moisture stress because increase in temperature in the pre-monsoon and monsoon season without adequate rainfall increases the evapotranspiration which leads to a soil-moisture deficit and limits tree growth (Fritts, 1976; Cook et al., 2003; Yadav et al., 2004). Other studies from the 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). Most of these studies were carried out in the areas much lower than treeline ecotone. Similarly, Yadav et al. (2004) obtained a negative as well as weakened relationship between the mean temperature of the summer months and growth of *A. spectabilis* from treeline sites of the western Himalaya. In the present study, responses of radial growth of *A. spectabilis* to minimum and maximum temperatures in the current year were in the opposite direction. This indicated to the prevalence of threshold temperature above or below which the responses become less sensitive to temperature or nonlinear to inverted U-shaped relationship (Paulsen et al., 2000; D'Arrigo et al., 2004; Yadav et al., 2004; Kullman, 2007).

In this study, the radial growth of *A. spectabilis* was less strongly correlated with precipitation, having significant negative correlation only with February precipitation. As precipitation in these months falls in the form of snow, high snow accumulation delays the growth initiation, shortening the growth period and ultimately resulting in the formation of a narrow ring. A deep snow pack in late winter has been shown to effectively reduce radial growth rates by maintaining low soil temperatures and delaying initiation of cambial expansion (Fritts, 1976; Pederson et al., 2004). Above-average moisture during the June of the previous year positively affects the current year's growth because above-average moisture during summer and early autumn may promote storage of carbohydrates and bud formation, thus enhancing growth during the following year (D'Arrigo et al., 2001; Fritts, 1976). The weak correlation of *A. spectabilis* radial growth with the precipitation also might be due to its sensitivity to temperature compared to precipitation. Conversely the weak correlation could be due to variation in the precipitation between the sampling sites and the local stations because in the Himalaya precipitation fluctuates greatly, even within a small geographic area (Barros et al., 2004).

The relationship between regeneration of *A. spectabilis* and the monthly maximum temperature of January–December of the current year was positive while the relation was negative with the monthly minimum temperature of the current year, indicating that low temperature adversely affects seedling survival. Severe soil frosts during cold winters were considered to be critical factors in the control of seedling survival by causing needle and shoot desiccation or fine-root mortality (Körner, 2003; Pederson et al., 2004; Kullman, 2007). Since extremely low cool-season temperatures facilitate the formation of abrasive ice crystals that physically damage trees and as a result often limit establishment at the treeline, this research also supports other recent studies documenting the critical impact of warmer winter temperatures on increased tree establishment in the high-elevation ecotones (Kullman, 2007; Kullman and Öberg, 2009; Harsch et al., 2009). The regeneration of *A. spectabilis* was positively correlated with the precipitation of May–August months. The positive relationship with the precipitation of these summer months implies that as the temperature had already attained the minimum threshold required for growth, high rainfall aids the survival and growth of seedlings and saplings. During summer months the temperature in the study area would often be high. So, low rainfall may create a desiccation situation and will have a stronger effect on recruitment because germinants are more sensitive to drought stress (Hughes et al., 2009; Fajardo and McIntire, 2012). Comparing with the past long-term reconstructed climatic data (Cook et al., 2003), the regeneration of *Abies* seems to be good during the episode of warm winter and cool summer. Hence, temperature plays a crucial role in growth and regeneration of *A. spectabilis* at the natural climatic treeline of the Himalaya.

From a similar study at the timberline on the Tibetan side of the Everest region, Lv and Zhang (2012) found that *A. spectabilis* recruitments in 5-year classes were positively correlated with their corresponding monthly mean air temperatures in June and September and with Palmer Drought Severity Index in June. The relationship was inverse for regeneration and ring width. From a study in a treeline on the southeastern Tibetan Plateau, Liang et al. (2011) found a significant positive correlation between the Smith fir (*Abies georgei* var. *smithii*) recruitment and both summer and winter temperatures. Wang et al. (2006) reported that several consecutive years of high minimum summer temperature and spring precipitation was the main factors favouring the establishment of *Picea schrenkiana* following germination within the treeline ecotone in the central Tianshan mountains.

Due to the lack of young seedlings and saplings as well as long climatic data, we could not calculate the climatic variables limiting growth and regeneration of *B. utilis*. However, in a recent study in birch timberlines from the Nepal Himalaya including our study site, Liang et al. (2014) using CRU grid-based data found a significant positive relationship between tree-ring width chronologies of *B. utilis* and precipitation in May and the pre-monsoon (MAM) season and a less strong negative relationship with temperature. They concluded that Himalayan birch growth at the upper timberlines is persistently limited by moisture availability during the pre-monsoon season. The poor regeneration and lack of recent shifting of the *B. utilis* in the area might result from the increasing moisture stress (Liang et al., 2014) as available precipitation data from the nearby station have shown a decreasing trend in the precipitation. In addition to the influence of climate change, the lack of recent regeneration of the *B. utilis* seedlings could be due to the influence of increased canopy cover by its own and associated tree species as well as dense shrub scrub because *B. utilis* seedlings could not establish under their own closed canopy even if they produce viable seeds (Shrestha et al., 2007) because the birch seedling growth is facilitated by direct sunlight (Shrestha et al., 2007; Hughes et al., 2009).

4.3 Treeline dynamics with climate change

The relationships between regeneration, treeline shifts and climate change may be more complex because climate may affect tree recruitment and treeline advance rate in different ways (Camarero and Gutiérrez, 2004; Wang et al., 2006; Kirdyanov et al., 2012). A treeline ascent implies several consecutive processes: production of viable seeds, dispersal, availability of adequate regeneration sites, germination, seedling survival and persistence until the individual reaches adulthood (Wang et al., 2006; Kullman, 2007). Climate variability affects all these sequential stages, but the same climatic variable can enhance one of these processes while inhibiting another one (Camarero and Gutiérrez, 2004; Wang et al., 2006). At a global scale, treelines are considered to be constrained primarily by growing season temperature (Körner and Paulsen, 2004). However, at many alpine treeline ecotones, both winter and summer temperatures are often key constraints on tree recruitment (Harsch et al., 2009; Liang et al., 2011) including other local site conditions, species' traits and feedback effects (Danby and Hik, 2007; Batllori and Gutiérrez, 2008). In the present alpine treeline study the establishment of the *A. spectabilis* is also controlled by both winter and summer climatic events.

An increasing number of studies have demonstrated that tree population density at treelines can respond quickly to rising temperatures (Camarero and Gutiérrez, 2004; Kullman, 2007; Liang et al., 2011) compared to the changes in treeline position because of the great longevity and phenotypic plasticity of tree individuals (MacDonald et al., 1998; Lloyd, 2005). If temperature is the primary and dominant driver for both recruitment and growth, these processes should be positively synchronized (Fajardo and McIntire, 2012). Some previous studies at treelines found concurrent synchronies (MacDonald et al., 1998; Batllori and Gutiérrez, 2008) and lagged synchronies of tree growth and regeneration in both positive and negative directions with climate change (Fajardo and McIntire, 2012). We found a synchronous regeneration of *A. spectabilis* in the treeline ecotone with climate warming. The climatic conditions that enhance radial growth of *A. spectabilis* were almost similar to the climatic conditions that enhance regeneration with slight variation in some months, which is similar to the findings of other studies (Szeicz and MacDonald, 1995; Camarero and Gutiérrez, 1999). In this study both the recruitment and radial growth of *A. spectabilis* was found to be associated positively with winter temperature and negatively with summer (May–August) months' mean and minimum temperature.

In spite of the regeneration of *A. spectabilis* above the existing treeline, the pace of future treeline shifting with climate change may not necessarily be the same because a seedling takes many years from establishment to reach its tree height (in the treeline, *Abies* took more than 30 years to reach 2 m height) and then to develop into a forest stand (Lloyd, 2005). On the other hand, there are no seedlings of *B. utilis* in and above the treeline. It will take several decades for newly established *Betula* seedlings to develop and form a treeline even if they establish now. As *A. spectabilis* in the treeline is more responsive to temperature change, an advance of this at the natural treeline of the Himalaya with climate change may continue if a long-term warming trend stimulates growth frequently enough even in cooler years or if low temperature events/periods which limit growth and regeneration are insignificant or if there would not be water deficit in plants which could offset the expected positive effects from temperature increase in tree establishment, growth and the upslope advance of treeline (Paulsen et al., 2000; Daniels and Veblen, 2004; Wang et al., 2006; Kullman and Öberg, 2009). In the case of *B. utilis*, Liang et al. (2014) reported that the birch treeline of the Himalaya is a rare case of a drought-induced alpine timberline and Himalayan birch at its upper distribution boundary is increasingly at risk of survival. Therefore, downslope range shift may occur as a response to global-change-type droughts (Liang et al., 2014). With the supportive evidence of differential life history, regeneration condition and the species-specific response of these two treeline species to climate change, it is clear that, in addition to treeline position, the community structure in the studied treeline in the Himalaya is going to change, if current climate change and response pattern continues.

5 Conclusions

The present study provided a recruitment pattern and dynamics history of Himalayan fir and Mountain birch at the high-altitude treeline of the Manaslu region, 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 year^{-1}. In spite of upward migration of *B. utilis* up to the mid-20th century, its upper distribution limit has been stagnant in recent years. The regeneration of *A. spectabilis* was positively related with monthly maximum temperature in most of the months of the current year and precipitation in May–August although the growth of the *B. utilis* can be also limited by pre-monsoon precipitation (Liang et al., 2014). Spatial and temporal variations in age structure and regeneration pattern 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 climate change and the studied treeline is changing. Studies incorporating multiple species and covering other proxy evidence like pollen from lake sediments could enhance our understanding of spatio-temporal treeline and vegetation dynamics in association with climate change.

The Supplement related to this article is available online at doi:10.5194/cp-10-1277-2014-supplement.

Acknowledgements. NAST provided a PhD fellowship to the first author. We are grateful to the National Trust for Nature Conservation for the permission to conduct this study at MCA. We thank Arbindra Shrestha, Janardan Mainali and local field assistants for their help during field work. Amalava Bhattarcharyya, Moinuddin Ahmed, Kumar Mainali and Madan Krishna Suwal provided with valuable suggestions in improving the paper and plotting the figures. Russell E. Train Education for Nature Programme, WWFUS provided a professional grant to the first author to participate in dendrochronology training in China. APN and PAGES supported participation in the PAGES Goa 2013 meetings. We are grateful to the four anonymous reviewers, Thorsten Kiefer and Anne-Laure Daniau for their constructive comments.

Edited by: A.-L. Daniau

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GAIRE ET AL (2015), *FUUAST J. BIOL.*, 5(1): 1-11

STUDY OF TREELINE ECOTONE TO ASSESS LONG-TERM IMPACT OF ENVIRONMENTAL CHANGE IN MT. EVEREST REGION, NEPAL HIMALAYA

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Abstract

Treeline is an excellent bioindicator of climate change impacts on high altitude biota. However, very few studies on the biological impacts of climate change have been reported from Nepal due to the lack of baseline information. This study of treeline ecotones in Mt. Everest region, Nepal Himalaya aims to prepare baseline information on structure and position of treeline to monitor the response of the ecotone to environmental change. This study was carried out at three treeline sites of Sagarmatha (Mt. Everest) National Park, in eastern Nepal Himalaya. Two to four belt transect plots (size: 20m wide, 100-190m long) were laid in each sites which included treeline as well as tree species limit. The present position of treeline with associated tree species composition was recorded and the position of each tree was mapped. Tree species in the site were represented by *Abies spectabilis*, *Betula*, *utilis*, *Juniperus recurva*, *Rhododendron campanulatum*, *Salix* sp. and *Sorbus microphylla*. Irrespective of the sites, *R. camapanulatum* was found growing at the highest elevation followed by *S. microphylla, A. spectabilis* and *B. utilis*. The population density ranged from 83 to 400 plants/ha with average density of 27 and 127 plants/ha for *Abies* and *Betula*, respectively. Size class distribution revealed an inverse-J shaped to multimodal bell shaped (DBH and Height) distribution indicating a situation of continuous to sporadic regeneration depending on the species and sites. As the size-class distribution graphs presented different shapes for different species and different sites, it is concluded that there exists a dynamic nature of the treeline ecotones and the species have site-specific and species-specific regeneration conditions. This study is expected to make a reference baseline for long term monitoring of treeline ecotones.

Introduction

Rapidly occurring environmental change including climate change has many bio-physical impacts, including shifting in geographic ranges, seasonal activities, migration patterns and abundances of species, and species interactions (Root *et al*., 2003; Chen *et al*., 2011; IPCC, 2014). An alpine or polar treeline is the one of the most obvious vegetation boundaries that limits regional tree growth (Holtmeier, 2009; Körner, 2012). The position of an alpine climatic treeline is mainly formed due to strong growth limitation by low-temperature conditions (Körner, 1998; Körner and Paulsen, 2004; Holtmeier, 2009) among several other factors. Natural treeline ecotones are sensitive biomonitors of past and recent climate change as they respond the climate change by exhibiting variations in position, structure and composition (Camarero and Gutiérrez, 2004; Holtmier and Broll, 2005; Harsch *et al*., 2009; Kullman and Öberg, 2009; Kirdyanov *et al*., 2012; Körner, 2012; Gaire *et al*., 2014).

The Himalaya, as compared to other regions, are more sensitive to environmental changes because of rapidly changing climate and associated impacts (Shrestha *et al*., 2012; IPCC, 2013, 2014). Vulnerability of ecosystems in the Himalaya to climate change is compounded by fragile topography and human activities, so prediction of future climate change impacts is complicated (Ferrarini *et al*., 2014). There is a vast knowledge gap on various aspects of treeline formation and their dynamics in the Himalaya (Schickhoff, 2005; Dutta *et al*., 2014). Available few studies from the treelines from Himalaya have reported increased tree density as well as an upward movement of the tree species limit (Dubey *et al*., 2003; Gaire *et al*.,2011, 2014).

The Sagarmatha (Mt. Everest) National Park (SNP), a natural world heritage site, is an important place due to its unique topographical, cultural and biological significance. However, the area is widely affected by climate change with several known impacts including shrinkage of permafrost areas (Fukui *et al.*, 2007), rapid recession of glaciers, formation and or increased size of glacial lakes (Fujita *et al*., 1998; Bolch *et al*., 2012; Thakuri *et al*., 2014). Impacts on biological processes like range and distribution shift including treeline dynamics are also expected but studies on these aspects are limited (Bhuju *et al*., 2010; Ferrarini *et al*., 2014). In addition to the impacts of climate change, forest and biodiversity of the region is also influenced by anthropogenic activities (Byers, 2005;Garbarino *et al*., 2014). In order to assess the impact of climate change and other anthropogenic activities in the natural biological community and predict their future distribution, it is very essential to know the current status of the forest and vegetation. Therefore, in this study, we aimed to (i) ascertain the present position of upper forest, treeline, and species limits, and (ii) record the species composition and characterize the stand structure of treeline ecotones in SNP.

Materials and Methods

Study Area: Established in 1976, SNP occupies an area of 1,148 km^{2}and is extended from 2,845 m (at Jorsale) to 8,848 masl (top of the Mt. Everest) (Bhuju *et al*., 2007). It is the country's first national park that was included in UNESCO list of World Natural Heritage Sites in 1979. In the north, SNP is linked with the Qomolangma National Nature Preserve of Tibet and extends to the DudhKosi River in the south. Most of the park area is very rugged and steep terrain cut by deep rivers and glaciers. The park, as an ecological entity in the highest region of the world, is scientifically very unique and offers opportunities for multiple aspects of research in a natural laboratory.

The climate in Sagarmatha region has extreme contrast between the humid southern slope influenced by the Indian summer monsoon and arid valleys in the northern slope under the desiccation effects of the Himalaya. About 80% of the annual precipitation occurs in the monsoon season (June to September) and rest of the year is fairly dry. Precipitation is low as the park is in the rain shadow of the Karyalung-Kangtega range to the south. Annual precipitation is 984 mm in Namche Bazar (Elevation 3,440 m)and it decreases with the elevation and comes around 516 mm per year at 5050 m at Pyramid lab (Jha, 2010; Thakuri *et al*., 2014).

Land cover classification shows that large area of land in the SNP is barren land (65.6%) most of it is above 5000 m, and less than 10% is forested area (Salerno *et al*., 2010). Six of the 11 vegetation zones described by Dobremez(1972) for the Nepal Himalaya are represented in the park: upper-temperate (2501- 3000 m), lower sub-alpine (3001- 3500 m), upper sub-alpine (3501 - 4000 m), lower alpine (4001- 4500 m), upper alpine (450 - 5000 m) and Nival (above 5000 m) (Bhuju *et al*., 2007).

Fig.1. Location map of the study area and study plots in the Sagarmatha National Park, Nepal Himalaya

Field visit and data collection: For this study, the treeline is defined as the high elevation region up to where 2 m tall trees can be found, and the species limit is defined as the highest position to which seedlings, saplings, or trees of the tree species are present.

Fieldwork was carried out during May-June in 2012 and 2013. After careful observation in transect walk at the treeline ecotones of three sites of SNP namely Pangboche, Dole and Phortse, the upper species limits of *A. spectabilis* and *B. utilis* in each site were ascertained. Two to four altitudinal transect plots (20m wide and 100-

190 m long) were marked at each sites in area where the treeline ecotones were as natural as possible. The plots were oriented with their longer side parallel to the maximum slope and covered the current species limit and treeline ecotone (Fig.1).The transect plots at the Dole, Phortse and Pangboche treelines were named as D1 and D2, PH1 and PH2, and P1 to P4, respectively. The aspects of the sampling site cover north-east, north-west and North facing slopes (Fig. 1). The length of the plots was determined based on the site conditions and distribution of the plants in the ecotones to capture the site characteristics of the area in our sampling. Individual plants were categorized and enumerated into three height classes: trees (>2 m), saplings (0.5-2 m) and seedlings (<0.5 m) (Wang *et al.*,2006; Gaire *et al.*, 2011).

Census survey was carried out in each plot to count the number of all individuals except *Rhododendron campanulatum* individuals. For every individual, their geographic location in the plot (latitude, longitude, and altitude using Garmin e-trex GPS); size (diameter at breast height (DBH), height), growth form and species were recorded. The regeneration condition was determined by observing size class distribution (Wangda and Ohsawa, 2006; Lv and Zhang, 2012). The treeline dynamics was analyzed by observing the position of trees, saplings, and seedlings as well as the size class distribution. Various descriptive statistics (Average, SD, max, range) were calculated in the Microsoft excel and SPSS software.

Results and Discussion

Species composition and geo-referenced treeline position: Treeline ecotones of the study area were formed by almost the same species with slight variation between different aspects. In Panboche, the treeline was formed by *Abies spectabilis, Betula utilis, Juniperus recurva, Rhododendron campanulatum* and *Sorbus microphylla* while in Dole and Phortse *Salix* sp. has also been recorded in addition to the previous five species. The treeline of the north and north-west facing slope of the Langtang National Park is formed by same tree species (Gaire *et al*., 2010) as in the north to north east facing in Manaslu Conservation Area (Gaire *et al*., 2014) where *J. recurva* and *Salix* sp are not present. In addition to *Abies* and *Betula*, the *Quercus semecarpefolia* also forms treeline community in the western Himalaya (Rai *et al*., 2012). Broadly, the treelines of the Himalayas are formed by deciduous species like *Betula* and *Larix*, and evergreen species like *Abies*, *Juniperus*, *Picea*, *Pinus* and *Rhododendron* (Miehe *et al*., 2007).

Table 1 presents the position of tree and species limit of the major treeline forming species i.e. *A. spectabilis* and *B. utilis*. From the field exploration in Dole it was found that *A. spectabilis* species limit was at 4123 m asl (27° 51’ 27.4’’ N and 86° 43’ 43.3’’ E) in D1 and 4141 m asl (27° 51’ 39.8’’ N and 86° 43’ 50.1’’ E) in D2 while *A. spectabilis* tree limit was found at 4105 masl (27° 51’ 31.6’’ N and 86° 43’ 47’’ E) in D1and 3996 masl in D2. In both transects the seedlings and saplings are at higher elevation than that of adult individuals. In D2 transect (190 m long) only seedling and sapling individuals of the *Abies* were recorded. *Betula* tree and species limit at Dole was found at same elevation i.e. 4103 m asl (27° 51’ 31.6’’ N and 86° 43’ 47’’ E) in D1 and 4132 m asl (27° 51’ 40.3’’ N and 86° 43’ 50’’ E) in D2. No *Betula* seedling was recorded in the plots. *Betula* species limit was lower than that of *Abies*. In D2, large numbers of *Sorbus*, *Salix* and *Rhododendron* individuals compared to other two species were recorded.

Abies spectabilis tree limit at Phortse was found at 4062 masl (27° 51.46’ N and 86° 44.859’ E) in PH2 while *Abies* was absent in PH1. *Betula* tree and species limit was found at 4099 m, asl (27° 51.483’ N and 86° 44.936’ E) and 4102 m, asl (27° 51.477’ N and 86° 44.925’ E) in the PH1. *Betula* species limit was higher than that of *Abies* in Phortse. Irrespective of the plots, *A. spectabilis* species limit (Elv. 4141 m asl 27° 51’ 0.5’’ N and 86° 47’ 54.6’’ E) was at higher position than its tree limit (Elv. 4134 m asl, 27° 51’ 3.7’’ N and 86° 47’ 58’’ E) in Pangboche while *Betula* species and tree limit was at lower elevation than *Abies* limit. The variation in the position of the species limit and treeline of *A. spectabilis* might be due to variation in the aspect and topographic condition as well as its recent dynamics. The position of *S. microphylla* in SNP was higher than that of *Abies* and *Betula* in most of the sites. Similar trend was observed in Langtang and Manaslu region (Gaire *et al*., 2010, 2014).

Table 1. Position of treeline and species line of *Abies spectabilis* and *Betula utilis* in Sagarmatha National Park, eastern Nepal Himalaya.

Tree/species limit	***Abies spectabilis***			***Betula utilis***		
	Dole	Phortse	Pangboche	Dole	Phortse	Pangboche
Species limit(m asl)	4141	4064	4141	4132	4102	4115
Tree limit (masl)	4105	4062	4134	4132	4099	4115

The position of the treelines are the result of the interactions of several biotic and abiotic factors (Holtmeier, 2009; Körner, 2012), so their position and species composition varies across the world or within a region (Körner, 1998; Miehe *et al*., 2007). In Nepal, the treeline position varies between the eastern, central and western region with decreasing trend from east to west (Schickhoff, 2005). Generally, the upper treeline elevations in the Hindu Kush-Karakoram-Himalaya (HKH) region increases along NW-SE gradient and a peripheral-central gradient from the Himalayan southern slope to the Great Himalayan range and the Tibetan highlands (Schickhoff, 2005). Along the western slope of Mt Annapurna, the upper timberline (*B. utilis*, *R. campanulatum*) at north-facing slopes rises to 4000-4100 masl and to even 4400 masl on the Nilgiri northern slope (Schickhoff, 2005). However in the Kalchuman Lake area of Manaslu, *A. spectabilis* treeline was found at 3907 masl and the *B. utilis* treeline at 4003 masl (Gaire *et al*., 2014) while at the Lauribinayak of Langtang *Abies* treeline was observed at about 3900-3950 masl (Gaire *et al*., 2011, Shrestha *et al*., 2015).

Community structural parameters of treeline forming species

Table 2. Population density of the treeline forming species in Sagarmatha National Park, eastern Nepal Himalaya

SPECIES	Population density (plants/ha)				
	Dole		Phortse		Average
	D1	D2	PH1	PH2	
Abies spectabilis	57	14	0	35	27
Betula utilis	19	8	210	270	127
Juniperus recurva	7	0	0	30	10
Sorbus microphylla	0	100	15	40	39
Salix sp.	0	69	0	25	24
Total density	83	191	225	400	225

The treelines we investigated are not monospecific but always mixed. Population density varies within and between sites and species. The average population density found was 225 plants/ha which ranged from 83 to 400 plants/ha. The average *A. spectabilis* density (27 plants/ha) was lower than that of *B. utilis* density (127 plants/ha) because the treeline site of the Phortse was dominated by birch trees. In this total population density, *R. campanulatum* is not included therefore plots density will be increased if we include it. The tree density in a treeline of Panboche area is higher than present record (Bhuju *et al*., 2010). Similarly, in a study along the timberline ecotones (3100-3400 masl) in Kedarnath Wildlife Sanctuary, western Himalaya, Rai *et al*. (2012) found the total tree density ranged from 340 to 780 trees/ha. The density of the *A. spectabilis* recorded in this study is low as compared to the density observed in other treelines like Pangboche in SNP (Bhuju *et al*., 2010), Lauribinayak in Langtang (Gaire *et al*., 2011), Kalchuman area of Manaslu Conservation area (Gaire *et al*., 2014) and Western Himalaya of India (Rai *et al*., 2012). Average *Betula* population density in present study is lower than treelines in Pangboche, SNP, Lauribinayak, Langtang and Manang (Shrestha *et al*., 2007). However, population density of *Betula* in Phortse was higher than that observed in the Pangboche by Bhuju *et al* (2010) and Langtang (Gaire *et al*., 2010). The *Betula* density of present study is lower than pure birch timberline but higher than mixed subalpine and timberline area of western Himalaya (Rai *et al*., 2012). The variation of this population density might be associated with the variation in the topoclimatic conditions, elevation of the plots and growing/succession stage of the treeline in the different regions of the Nepal Himalaya (Schickhoff, 2005; Shrestha *et al*., 2007; Rai *et al*., 2012).

Size class distribution: Distributions of the various structural parameters like plant height, basal diameter, DBH were studied. Figures 2 to 5 show distribution of the DBH and heights of the tree individuals in Dole region. The average height of *A. spectabilis* at Dole was 1.63 m ± 1.73 SD. Since maximum height was observed to be 5.5 m, the small average height indicates dominance of lower heights individuals' i.e. seedlings and saplings. Similarly, the average height of *B. utilis* was found 4.51 m ± 3.38 SD. This indicates that the minimum presence of seedlings and saplings of *B. utilis*. The average DBH of *A. spectabilis* at Dole was 11.14 cm (SD = 5.74 cm, max = 20 cm) and DBH of *B. utilis* was 22.58 cm (SD = 19.8 cm, max = 76.0cm,). The average DBH and height of *A. spectabilis* was lower than *B. utilis* indicates that there is lack of small sized

Betula individuals. The average DBH and height of *A. spectabilis* was higher in D1 while that of *B. utilis* was found to be high in D2 (Fig. 2 and 3).

From the study it was found that the average heights of *A. spectabilis* at Phortse was 3.53 m (SD = 2.95 m, max = 8.0 m). Similarly, the average height of *B. utilis* was found 5.12 m (SD = 1.65 m, max = 7.6 m). The average DBH of *A. spectabilis* and *B. utilis* at Phortse was 17.33 cm (SD = 6.45 cm, max = 29 cm), 9.24 cm (SD = 4.61 cm, max = 28.0 cm) respectively. The average DBH and height of *A. spectabilis* was lower than *B. utilis* indicating presence of young individuals of *Abies*. The *A. spectabilis* was absent in the PH1 transect.

The average DBH of *Abies* in Dole and Phortse was lower than that observed in the Pangboche area of the SNP as well as treelines of the Langtang (Gaire *et al*., 2011) and Manaslu (Gaire *et al*., 2014). This might be due to the young growing condition as well as low population density. However, average DBH of *B. utilis* in Dole was higher than that observed in the treeline of the Pangboche area of SNP and area Kalchuman Lake area of Manaslu (Gaire *et al*., 2014) and but lower than Langtang (Gaire *et al*., 2010).

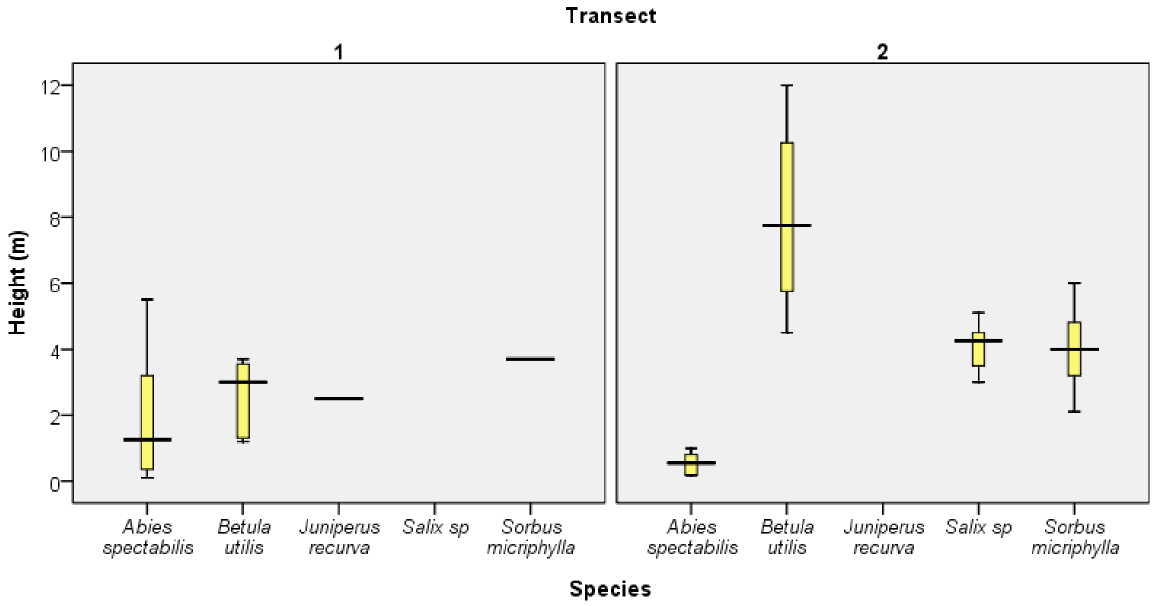

Fig. 2.Box and whisker plot of tree height in Dole, Sagarmatha National Park, eastern Nepal

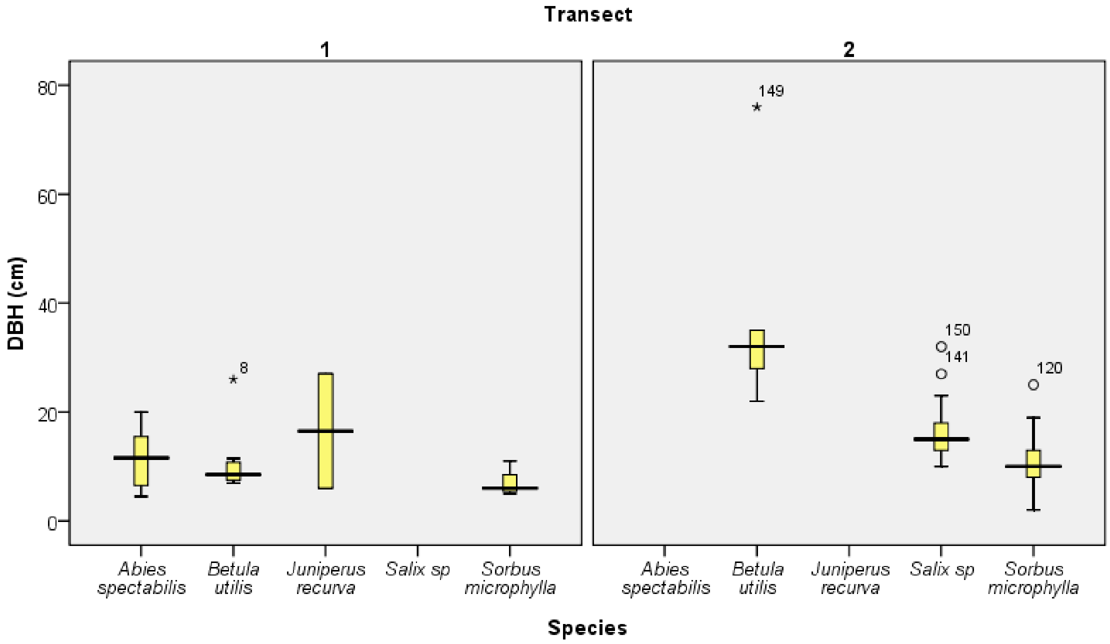

Fig. 3. Box and whisker plot of DBH tree species in Dole, Sagarmatha National Park, eastern Nepal.

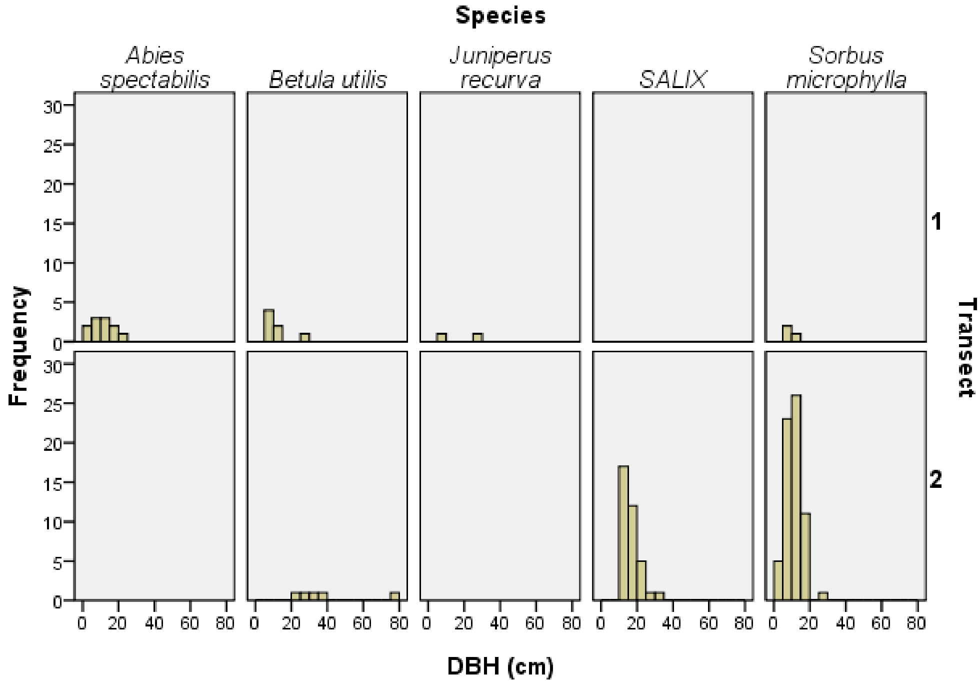

Fig.4. DBH class distributions of major tree species in Dole, Sagarmatha National Park, eastern Nepal

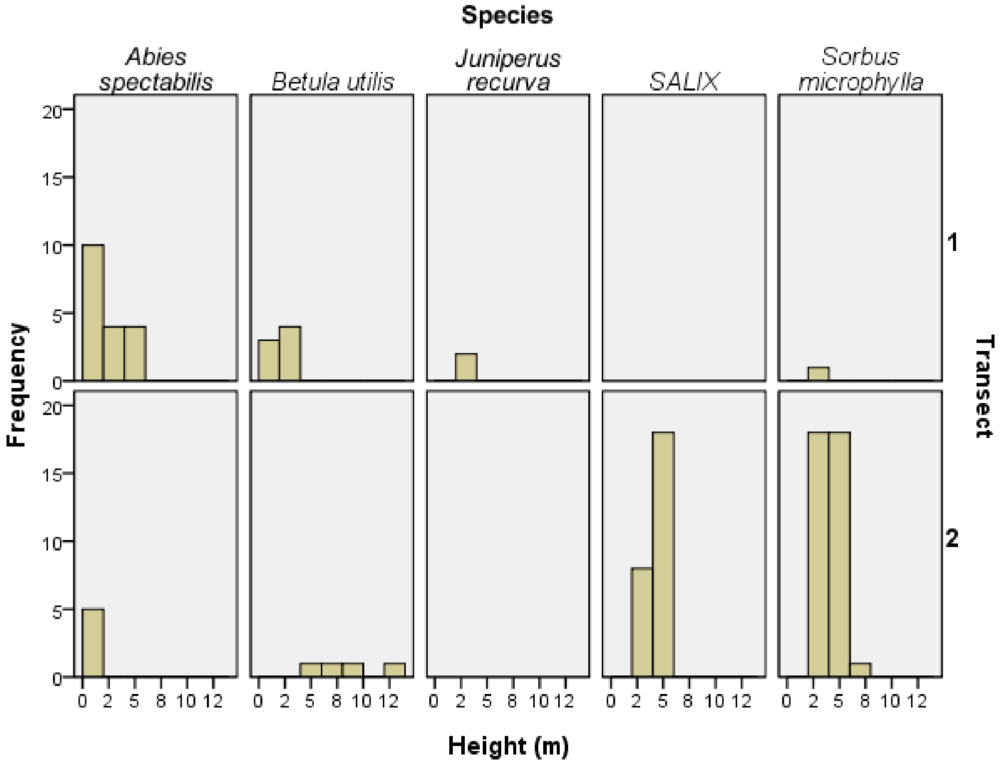

Fig.5. Height class distribution of tree species at Dole, Sagarmatha National Park, eastern Nepal

The box plot depicted a skewed distribution of the treeline forming individuals (Figs.3 and 6) indicating differential regeneration status of these species. Figure 4 presents the DBH class distribution in Dole. The DBH distribution of *A. spectabilis* shows unimodal bell shaped distribution in D1 with peaks at 5-15 cm. However, all individuals in D2 were smaller than breast height. DBH distribution of *B. utilis* in D1 is slightly similar to the inverse-J shape. However, DBH distribution of same species in the D2 shows sporadic pattern. Height class distribution includes all individuals and shows that there is better regeneration of *A. spectabilis* than *B. utilis* in recent years with slightly an inverse–J shaped distribution of *Abies* and bell shaped or sporadic type distribution of *Betula* (Fig. 5). Similar trends were observed in height class distribution. In case of *A. spectabilis* height class 0-2 m had highest number of individuals indicating recruitment of individuals in recent years.

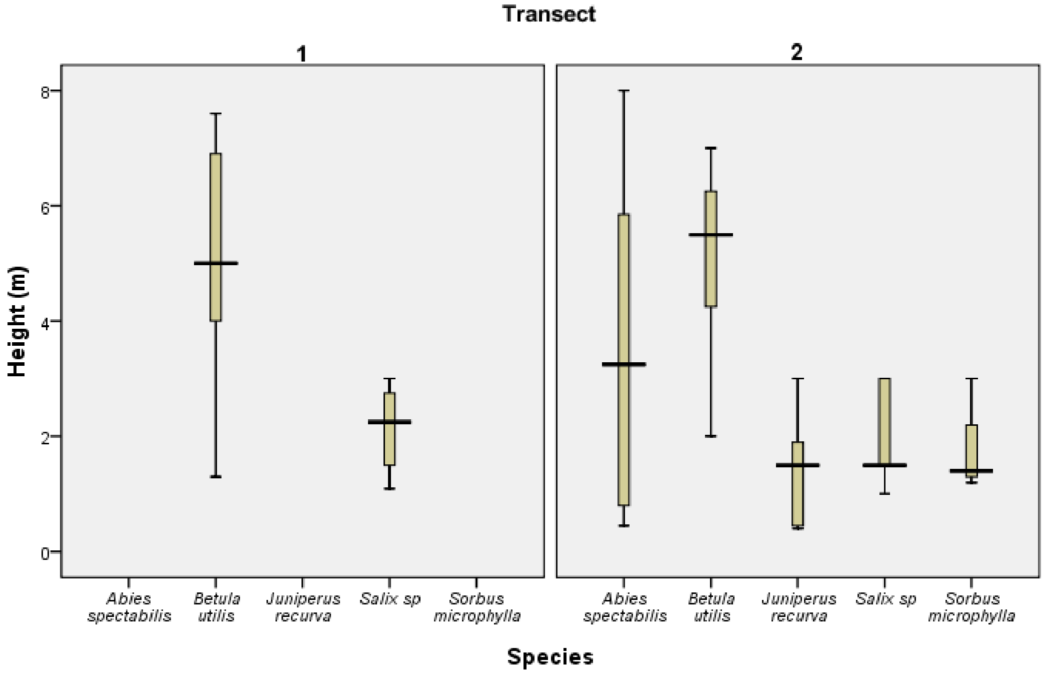

Fig. 6. **Box and whisker plot of DBH of tree species in Phortse, Sagarmatha National Park, eastern Nepal**

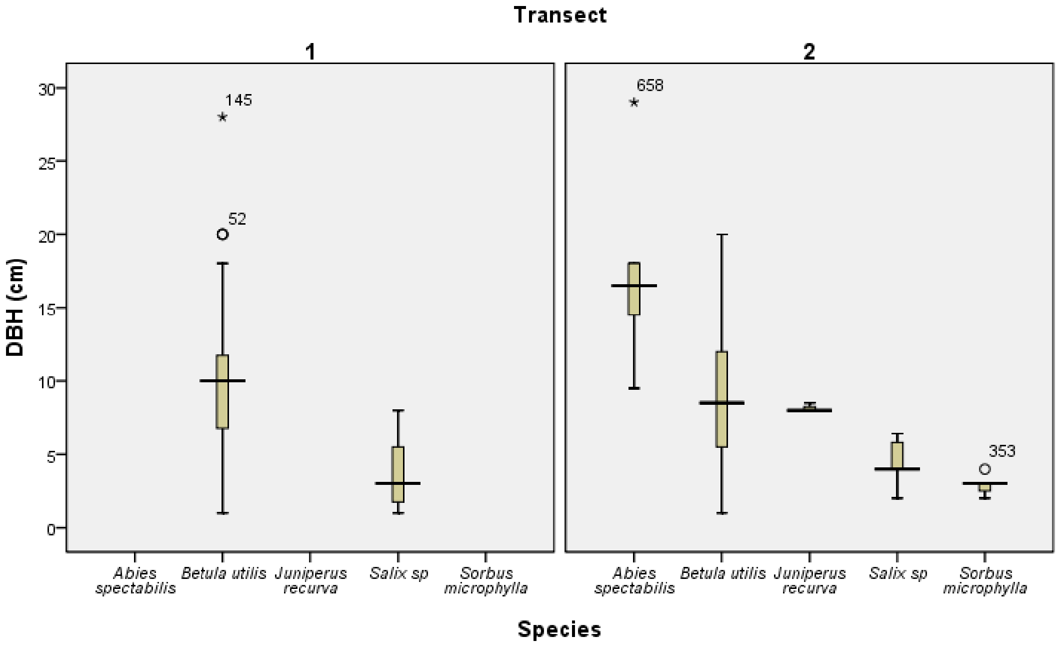

Fig. 7. Box and whisker plot of tree height in Phortse, Sagarmatha National Park, eastern Nepal

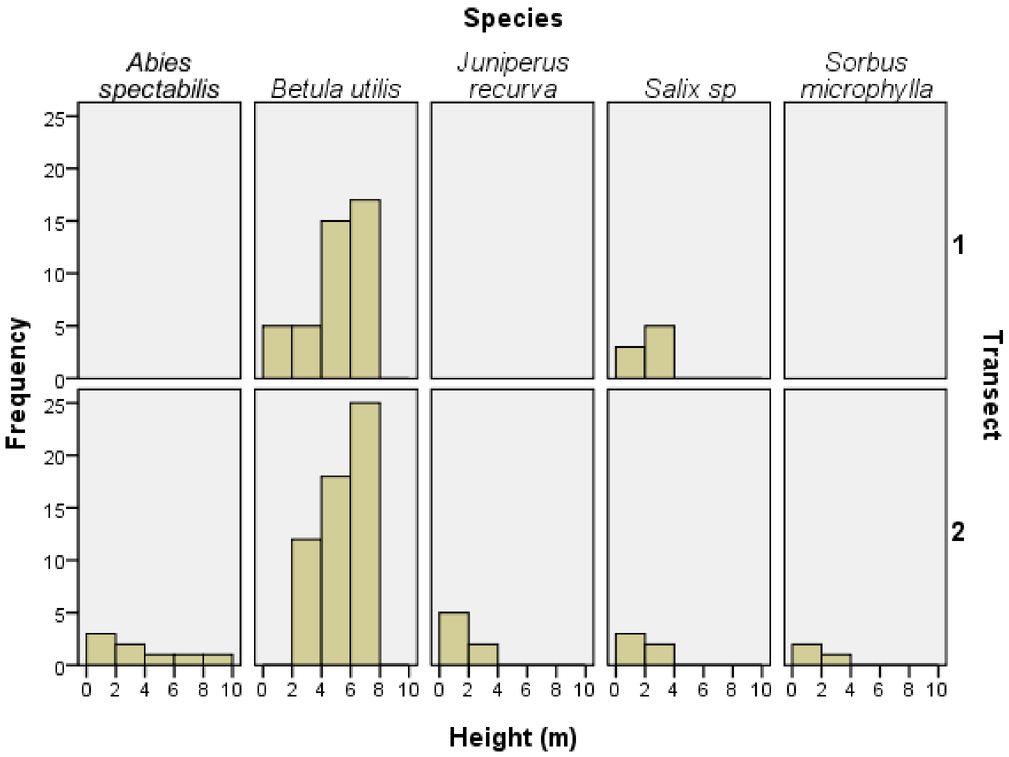

Fig. 8. Height class distribution of tree species in Phortse, Sagarmatha National Park, eastern Nepal

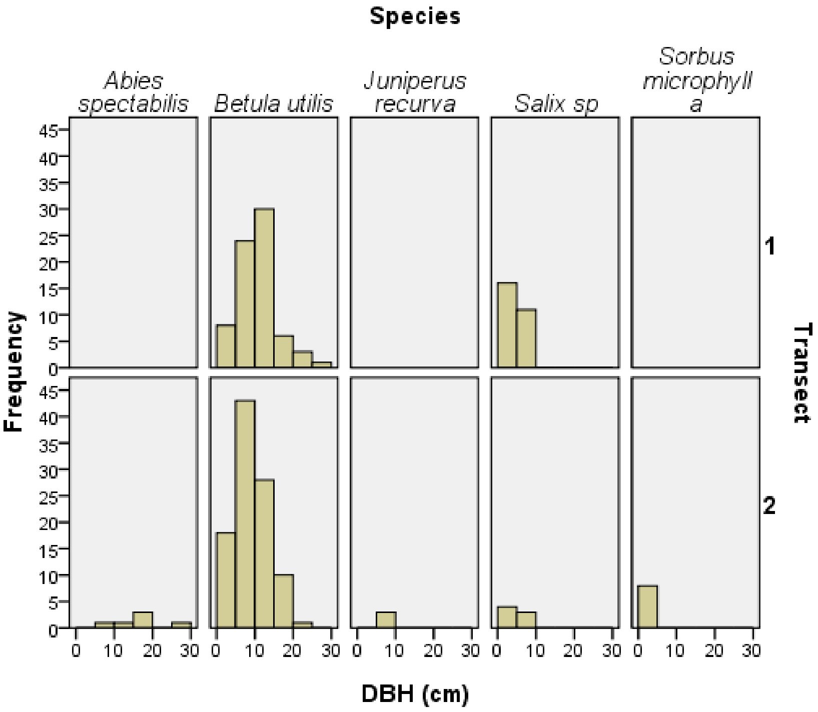

Fig. 9. DBH class distribution of tree species in Phortse, Sagarmatha National Park, eastern Nepal

Figures 6 to 9 show the distribution of the DBH and heights in Phortse. The distribution is asymmetric in shape indicating differential regeneration condition in the area. The DBH class distribution of *A. spectabilis* shows slightly unimodal distribution in the PH2 with peaks at 15-20 cm (Fig. 9); however, it was absent in PH1. DBH class distribution of *B. utilis* in PH1 is slightly unimodal with peak in 10-15 cm. The same species in the PH2 shows slightly an inverse-J shaped pattern indicating good regeneration compared to PH1. The height class distribution of *Betula* shows its growing stage. From overall analysis, it seems that the recent regeneration of *Abies* is good as compared to that of *Betula*.

The size class distribution of the tree species reflects its regeneration status (Wangda and Ohsawa, 2006; Lv and Zhang, 2012; Liang *et al*., 2011; Rai *et al*., 2012). In our study, the structural parameters not only varied between the plots but also between the species with the shape of DBH distribution from an inverse-J shaped to uni-to multi-modal bell shaped. In a study in treeline of Manaslu, the DBH class distribution of *A. spectabilis* shows a unimodal to bimodal distribution (Gaire *et al*., 2014). Such kind of differences in the DBH class distribution of *A. spectabilis* and *B. utilis* have been observed in other treeline ecotones in Nepal (Shrestha *et al*., 2007; Bhuju *et al*., 2010; Gaire *et al*., 2011) and Indian Himalaya (Rai *et al*., 2012), indicating site-and species-specific regeneration condition. Similarly at the *A. spectabilis* treeline near the Everest region on the Tibetan side, Lv and Zhang (2012) observed a multimodal DBH distribution with peaks 0-10 and 30-40 cm. The differential spatio-temporal regeneration pattern reflected in the multimodal size of age and/or DBH class distributions were also observed in various treelines sites of different mountains (Wang *et al*., 2006; Gou *et al*., 2012).The regeneration at the treeline can be sporadic or episodic (Cuevas, 2002; Lv and Zhang, 2012). The gaps in some diameter and height classes observed in the present study indicate that episodic regeneration during the favorable climatic period is the most common feature even in these treeline ecotones.

Conclusions

The present study provided geo-referenced position and community structure of treeline ecotones of the Sagarmatha National Park with special reference to Himalayan fir and Mountain birch in eastern Nepal Himalaya. Spatial and temporal variation in the regeneration patterns of the treeline species is evident from the size class distribution. This study will be a baseline reference to assess and long term monitoring of the impact of the environmental changes including climate change in the treeline vegetation of the Mt. Everest (Sagarmatha) National Park in Nepal Himalaya.

Acknowledgements

NAST provided PhD fellowship to the first author. We are thankful to Department of National Park and Wildlife Conservation, Kathmandu for the permission to conduct this study inSagarmatha National Park. We thank local staff of the SNP office at Namche and field assistants for their help during field work. EvK2CNR provided financial support for the fieldwork of the study. Comments provided by Uday Thapa helped to improve the manuscript. We are grateful to the reviewers for their valuable comments in the manuscript.

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Dendrochronologia xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Dendrochronologia

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Site- and species-specific treeline responses to climatic variability in eastern Nepal Himalaya

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ARTICLE INFO

Article history:
Received 31 August 2015
Received in revised form 25 February 2016
Accepted 1 March 2016
Available online xxx

Keywords:
Treeline dynamics
Climate change
Dendroecology
Sagarmatha national park
Nepal himalaya
Growth-climate response
Mt. Everest

ABSTRACT

Alpine treelines act as bio-indicators and bio-monitors of environmental change impacts in high elevation forests. This dendro-ecological study carried out in treeline ecotones in the Sagarmatha (Mt. Everest) National Park (SNP), eastern Nepal Himalaya, aimed to assess treeline dynamics and to understand the response of treeline forming *Abies spectabilis* (D. Don, Mirb) and *Betula utilis* (D. Don) to environmental change. At three treeline sites we placed two to four belt transects (size: 20 m wide, variable length) which bisected the treeline as well as the tree species limit. The results revealed spatio-temporally heterogeneous regeneration with a higher regeneration of *A. spectabilis* compared to *B. utilis*. Warm temperatures during summer (JJA) growing seasons combined with sufficient moisture favored the growth of *A. spectabilis* while moisture stress during spring seasons (MAM) mainly limited the growth of *B. utilis*. The regeneration of *A. spectabilis* was favored by high temperatures throughout the year with sufficient moisture. The climatic response of the regeneration of *B. utilis* was spatiotemporally different and variable. Results predict a changing community structure in the treeline in response to future environmental change. During the past 200 years, *A. spectabilis* shifted upward by about 0.93 m/yr and *B. utilis* by 0.42 m/yr, with stabilization during the second half of the 20th century at the majority of the sites. The recent stability in treeline position of both species at most sites indicated that in addition to favorable climate, species-specific competitive abilities during the recruitment phase, recruitment suppression in the Krummholz and dwarf scrub belts, and grazing determine regeneration success and treeline position in the region.

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1. Introduction

Treeline is one of the most highly studied vegetation ecotones in the world because of its sensitivity towards various environmental changes (Holtmeier and Broll, 2005; Holtmeier, 2009; Körner, 2012). As most climatic treelines are shaped due to low temperature limitation (Körner and Paulson, 2004; Körner, 2012), these ecotones respond structurally, positionally, and physiognomically to climate change and, particularly in recent decades, to temperature increase (Holtmeier and Broll, 2005; Harsch et al., 2009; Körner, 2012). However, the response of the treeline to climate change not only varies spatially and temporally but also in relation to treeline form and structure (Holtmeier, 2009; Harsch and Bader, 2011). Many studies have reported changes in the recruitment phases, and in the tree density as well as a shift to the higher altitudes or latitudes in response to long-term climate fluctuation (Harsch et al., 2009; Liang et al., 2011; Kirdyanov et al., 2012; Mamet and Kershaw, 2012; Öberg and Kullman, 2012; Hofgaard et al., 2013; Aakala et al., 2014). The dendroecological approach is very useful to calculate tree establishment and assess the response of forests, including the treeline, to various aspects of environmental perturbations (Fritts and Swetnam, 1989; Wang et al., 2006; Speer, 2010; Körner, 2012).

The Himalaya is a biologically, culturally, and ecologically significant mountain system. However, the region is more sensitive and vulnerable to climate change as the rate of change is more pronounced here compared to other regions (Shrestha et al., 2012; IPCC, 2013; Qi et al., 2013), and its vulnerability is exacerbated by a fragile and young geology. Several imprints of climate change are already observed in diverse sectors (Xu et al., 2009; Shrestha et al., 2012; Bolch et al., 2012; Telwala et al., 2013; Thakuri et al.,

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http://dx.doi.org/10.1016/j.dendro.2016.03.001
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Please cite this article in press as: Gaire, N.P., et al., Site- and species-specific treeline responses to climatic variability in eastern Nepal Himalaya. Dendrochronologia (2016), http://dx.doi.org/10.1016/j.dendro.2016.03.001

2014). The treelines of the Himalaya are mainly formed by the *Abies* sps, *Betula utilis*, *Juniperus* sps, *Pinus wallichiana*, *Larix* sps, *Rhododendron campanulatum*, *Sorbus* sps (Schickhoff, 2005; Miehe et al., 2007); most of them have proven dendrochronological potential (Bhattacharyya et al., 1992; Cook et al., 2003; Dawadi et al., 2013). Therefore, they provide a good opportunity to observe changes in community structure as well as their response to climate change. However, very limited research on the treeline of the Himalayan mountain range have been carried out, compared to the other mountain systems, and a knowledge gap exists in many aspect of its treeline formation and dynamics (Schickhoff, 2005; Xu et al., 2009; Dutta et al., 2014; Schickhoff et al., 2015). A few investigations, mostly regarding Indian Himalaya, using remote-sensing and repeat photography data have reported increasing density as well as an upward shifting of the treeline ecotone (Panigrahy et al., 2010; Bharti et al., 2012; Singh et al., 2012, 2013). Similarly, field-based studies have reported an increased tree density, stable but with potential for shifting, as well as upward shifting of the treeline (Dubey et al., 2003; Gaire et al., 2011, 2014; Lv and Zhang, 2012; Chhetri and Cairns, 2015; Schickhoff et al., 2015; Shrestha et al., 2015). Though limited, available studies have reported both temperature and moisture limitation for tree growth at the treeline (Körner and Paulson, 2004; Körner, 2012; Gaire et al., 2014; Liang et al., 2014; Schickhoff et al., 2015). Comparisons of how different species of a community respond to changing climatic conditions give an insight into future community composition and the potential formation of new communities. Therefore, this study takes a multiple species approach using dendroecological tools for an assessment of treeline dynamics.

Sagarmatha (Mt. Everest) National Park (SNP), a natural world heritage site and ecological body at the highest elevation of the world, offers opportunities for multiple aspects of research in a natural laboratory. The park is vulnerable to climate change and has already experienced rapidly increasing temperature but weakening precipitation (Qi et al., 2013; Salerno et al., 2015). The known impacts of this changing climate have included the shrinkage of the permafrost area (Fukui et al., 2007), melting of snow, rapid retreating of glaciers, and formation and expansion of glacial lakes (Benn et al., 2012; Bolch et al., 2012; Thakuri et al., 2014). Few studies have focused on the impacts on forest and biodiversity aspects (Bhuju et al., 2010; Ferrarini et al., 2014; Garbarino et al., 2014). Moreover, there is no study incorporating the response of multiple species of the treeline area to environmental (climate) change. The landscape of the area has been in continuous modification since the Sherpa people started to inhabit the area over 500 yrs ago and rapidly increasing tourism and climate change has increased the anthropogenic pressure in the area (Byers, 2005; Garbarino et al., 2014). Furthermore, the rangeland above the treeline are summer grazing lands and the existence of many settlements above the treeline makes it difficult to assess and predict the impacts of climate change in the region separately from the anthropogenic influence (Ferrarini et al., 2014; Garbarino et al., 2014; Gaire et al., 2015). Human settlement and grazing practices still take place inside the park. Therefore, this study aims to assess the treeline dynamics of the SNP area and to understand the response of treeline forming species to environmental change including climate change.

2. Materials and methods

2.1. Study area and climate

Situated in the northern part of Solukhumbu District in eastern Nepal, SNP (Est. = 1976, Area = 1148 km^2 Elevation = 2845–8848 masl) is the country's first national park included in UNESCO's list of World Natural Heritage Sites in 1979 due to its natural, ecological, and cultural significance (Bhuju et al., 2007). In the north, the Qomolangma National Nature Preserve of Tibet borders the SNP and it extends to the Dudh Kosi River in the south (Gaire et al., 2015). Most of the park area comprises very rugged and steep terrain cut by deep rivers and glaciers. Six vegetation zones, as described for the Nepal Himalaya by Dobremez (1975), exist within the park.

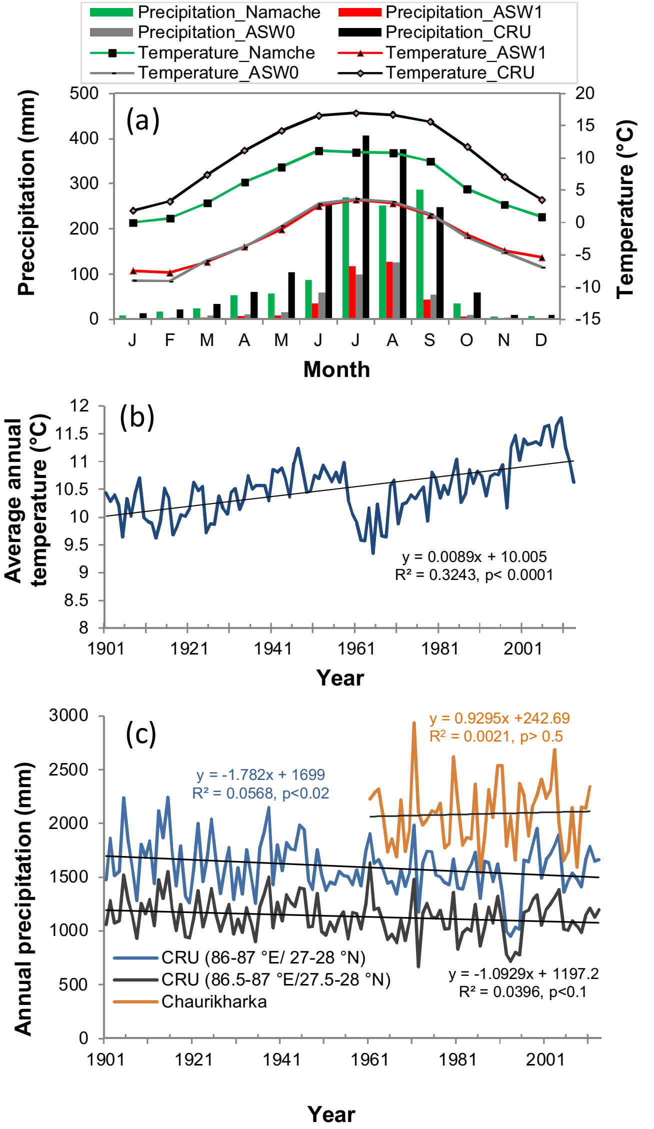

Fig. 1. Climograph of the Sagarmatha National Park area (a). Fig. 1a presents monthly average temperature and monthly total precipitation in local weather stations and CRU grid data. ASW0 and ASW1 are weather station's name situated near Pyramid lab in Sagarmatha National Park and CRU represents Climate Research Unit's grid climatic data. Annual trend of grid-based CRU mean temperature (b). Annual trend of grid-based CRU precipitation data with latitude and longitude of the area included and Chaurikharka station precipitation data (c).

The climate in the SNP region is semi-arid with significant differences between the humid southern valleys, under major influence of the Indian summer monsoon, and the arid northern ones affected by the desiccation effects of the Himalaya range. Precipitation in most of the park is low because it lies in the rain shadow of the Karyalung-Kangtega range. More than 80% of the annual rainfall occurs in the monsoon season (June to September) with heavy snow accumulation during winter (Fig. 1a). Annual precipitation is about 1000 mm in Namche Bazar (3440 m) and it decreases with elevation to approximately 500 mm per year at Pyramid lab (5050 m)

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(Fig. 1a, and Thakuri et al., 2014). Despite the fairly short and sparse meteorological records within the area, both a local-based analysis (Salerno et al., 2015) and the global CRU TS3.22 dataset (Harris et al., 2014) extracted using the KNMI climate explorer (Trouet and Oldenborgh, 2013) converge in describing a significant increase in temperature (Fig. 1b), mostly concentrated outside of the monsoon period together with a precipitation weakening (Fig. 1c) during the monsoon season.

2.2. Site-species selection, and data and sample collection

For this study, the treeline is defined as the highest elevation up to where 2 m tall trees can be found and the species limit is defined as the highest position to which seedlings, saplings or trees of the tree species are present (Gaire et al., 2011, 2014, 2015). The timberline is the upper limit of the subalpine forest (with canopy more than 30%).

Fieldwork for this study was carried out during May-June in 2012 and 2013. The treeline was explored in three sites: Dole, Phortse and Pangboche (Fig. 2). The treeline in the area was mostly composed of *Abies spectabilis* (hereafter only *A. spectabilis*) and *Betula utilis* (here after *B. utilis*) with *Sorbus microphylla* and *R. campanulatum* in the understory with some *Juniperus* and *Salix* in few places (Gaire et al., 2015). *Sorbus* and *Rhododendron* were dominant in the uppermost part of the treeline ecotone while *A. spectabilis* and *B. utilis* dominated the lower treeline and timberline regions (Fig. 2b–d). Two to four altitudinal transect plots (20 m wide and 100–190 m long according to the site and treeline position and settings) were marked out at each sites in areas where the treeline ecotones were as natural as possible (Fig. 2a). The plots were oriented vertically with their longer axis parallel to the maximum slope and covered the current species limit and treeline ecotone (Fig. 2b). The transect plots at Dole, Phortse and Pangboche treelines were named as D1 and D2, PH1 and PH2, and P1–P4, respectively. The study was mainly centered on northeast, northwest, and north facing slopes. Individual plants were categorized and enumerated into three height classes: trees (>2 m), saplings (0.5–2 m), and seedlings (<0.5 m) (Wang et al., 2006; Gaire et al., 2011, 2014, 2015).

For every individual, size (diameter at base (DB), diameter at breast height (DBH), and height), growth form, and species were recorded. To calculate the age of tree individuals, one or two cores per tree were collected at the stem base from the *A. spectabilis* and *B. utilis* trees. Additional cores were collected from larger trees at breast height to assess growth-climate responses. More than 350 tree cores were collected.

The ages of trees were calculated by tree core analysis, while those of seedlings and saplings of *A. spectabilis* 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; Gaire et al., 2014). Studies have shown that the whorl count method gives an accurate indication of the age of saplings and seedlings of *A. spectabilis* (Gaire et al., 2014; Chhetri and Cairns, 2015).

2.3. Population demography, regeneration, and treeline dynamics

The age obtained after crossdating was used for population demographic analysis after the necessary correction for years to core height and years to center of missed pith (Speer, 2010). Such correction was made using age-height 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; Batllori and Gutiérrez, 2008; Speer, 2010). For *B. utilis*, a regression analysis model between diameter at base (DB) and age was established (Age = 3.6102 × DB + 2.1; $R^2 = 0.82$, n = 65, $p < 0.0001$) incorporating cores from representative sample trees

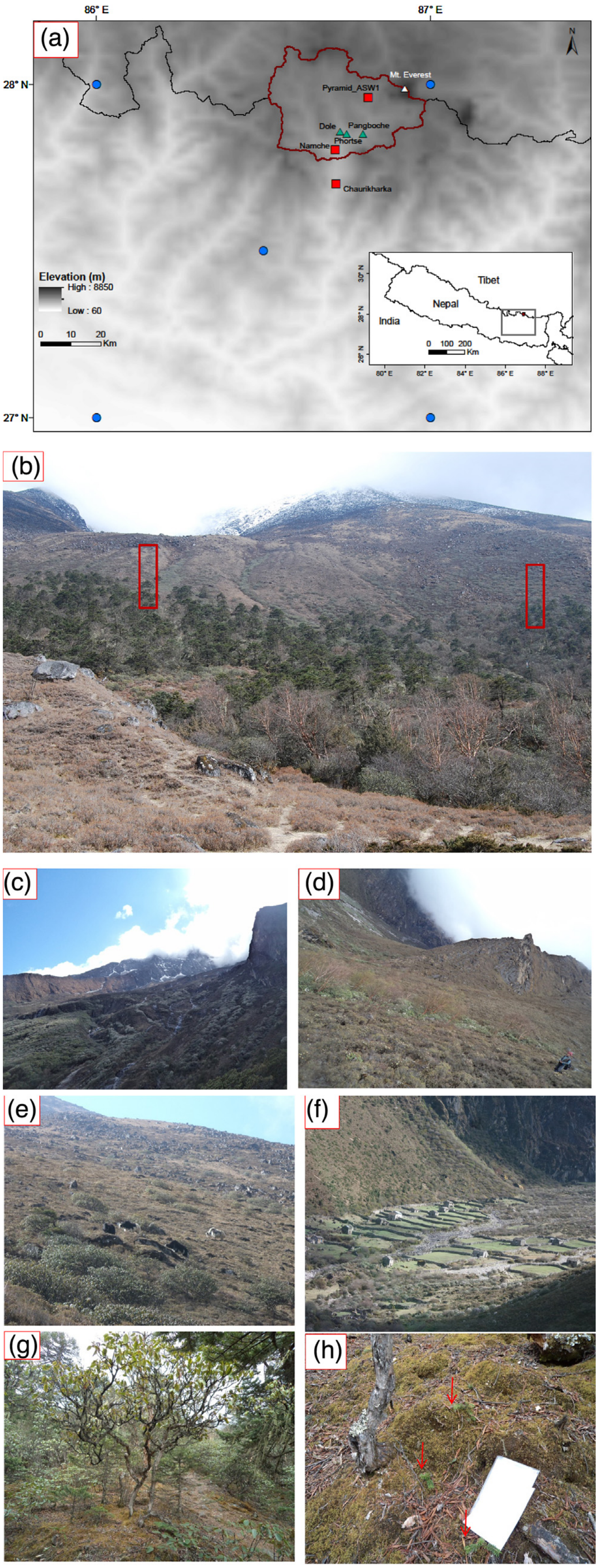

Fig. 2. Location map of the study area and study sites in the Sagarmatha National Park, Nepal Himalaya (a). Green triangles on the map represent sampling sites, red squares represent local meteorological stations, and blue circles denote CRU climate data grid points; the treeline ecotone at Pangboche with the layout of the transect plot denoted by red mark (b); Rhododendron Krummholz dominated treeline at Dole (c); and *Betula utilis* dominated treeline at Phortse (d); grazing at the treeline ecotone of the study area (e); summer grazing point and *Chaunri* sheds near to the

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spanning different DB classes. The ages of all *B. utilis* individuals from which cores were not taken was estimated based on this model.

The regeneration condition was determined by observing size class distribution (Wangda and Ohsawa, 2006; Körner, 2012; Lv and Zhang, 2012) using the a number of seedlings, saplings and trees individuals. Age histograms of the species were produced dividing them into their corresponding calendar year classes (10-year bin). Two sample Kolmogorov-Smirnov tests were carried out to determine the difference in temporal recruitment patterns between different species and sites. Treeline dynamics were analyzed by assessing the spatio-temporal distributions of tree, sapling, and seedling density as well as the elevation-wide age distribution. The upper species limit (treeline) expansion was studied by observing the age of each individual in the entire plot following Camarero and Gutiérrez (2004), Kirdyanov et al. (2012) and Gaire et al. (2014). In order to calculate the rate of treeline/species-limit shift, the maximum elevation of live individuals and the position of the oldest individual within each transect were determined. Then, the treeline or species limit shift rate (m/yr) was calculated by dividing the change in elevation (position) of the species limit by the time elapsed.

2.4. Tree cores analysis and chronology development

Core samples were prepared and analyzed using standard dendrochronological techniques (Fritts, 1976; Cook and Kairiukstis, 1990; Speer, 2010). All cores were air-dried and mounted on grooved sticks, sanded and polished using successively finer grits of sand paper to expose ring details to the cellular level. After carefully examining these samples under the microscope, each ring was counted and dated. Total ring width was measured to the nearest 0.01 mm with a LINTAB^{TM5} measuring system attached to a PC running TSAP-win software (Rinn, 2003). Crossdating was done using the alignment plotting technique in TSAP and by examining the chronology statistics (Rinn, 2003). Accuracy of crossdating and measurements were further checked using the COFECHA program (Holmes, 1983; Grissino-Mayer, 2001). Out of 5873 rings of *B. utilis* analyzed, 0.22% rings were missing from the tree ring series. Most of the absent rings were from the years of 2004 and 1999 with one each from 1992 and 1926. As we removed problematic samples, missing rings from the *A. spectabilis* tree ring series was found to be very rare. Cores that correlated poorly in COFECHA or were very young (less than 50 yrs old) were removed from the final data set prior to chronology development. Tree ring-width chronologies were developed using ARSTAN (Cook, 1985; LDEO, 2015). The standardization using ARSTAN removes both the geometric and other growth trends resulting from tree-to-tree competition and stand dynamics while preserving variability likely related to climate. We performed double detrending for *B. utilis*, first using a negative exponential curve and then using cubic smoothing splines curves of 20 years. For *A. spectabilis,* both double and interactive detrendings were tried. Interactive detrending using negative exponential, linear trends or a spline of 20 yrs. preserved more of the common signal. After detrending, individual timeseries were averaged using a bi-weight robust mean function (Cook, 1985). Chronology quality was estimated using rbar (Briffa, 1995) and expressed population signal statistics (Wigley et al., 1984). After checking for correlation, cores of each species from all sites were pooled together to make a composite chronology for each species.

2.5. Climate influence on tree growth and regeneration

The relationships between the tree-ring width residual chronology of each species and monthly average temperatures and total precipitation were analyzed by correlation functions for the period of 1901–2011 in the CRU gridded dataset TS3.22 and 1961–2011 for instrumental data using DendroClim2002 (Biondi and Waikul, 2004). As climate in the preceding growing season often influences tree growth during the following year (Fritts, 1976), we considered temperatures and precipitation data from June of the previous growth year until October of the current growth year.

To investigate the relationship between regeneration and climate, age data were first summed across five-year intervals to take into account uncertainties in age estimates (Wang et al., 2006; Gaire et al., 2014; Chhetri and Cairns, 2015) and then compared with monthly climate records compiled into five-year averages over the same period. Monthly climatic records (mean temperature and total precipitation) from the CRU gridded dataset (1901–1911) and precipitation data (1961–2011) from Chaurikharka station were used. Climate factors limiting regeneration were identified from simple linear correlation analysis between regeneration and climatic data.

3. Results and discussion

3.1. Population age structure

Population age structures of both species revealed temporal variation in regeneration and mortality rates. In some plots, the recruitment history extends back to the early eighteenth century, but most treeline ecotones experienced recruitment pulses during the early to middle of the 20th century (Fig. 3). The age class distributions of *A. spectabilis* populations revealed sporadic to continuous regeneration depending on the site. Age class distributions at Pangboche showed a slight peak in regeneration during the 1920s, 1940s and in recent decades (Fig. 3). Young individuals recruited after 1950s dominated the total population of *A. spectabilis* at Pangboche with 2001–2010 class being the dominant age class. However, the age histories of *A. spectabilis* at Phortse and Dole only goes back to the 1970s and 1950s, respectively, indicating that the treeline populations of these two sites are formed by very young individuals (Fig. 3).

Similarly, the population age of *B. utilis* at Pangboche extends to the 1830s having a sporadic age class distribution with a slight peak in 1940s (Fig. 3). After that, the regeneration of *B. utilis* decreases. There were very few young individuals in the total population. The age history of *B. utilis* at Phortse only goes back to the 1890s. However, the upper treeline (PH1) plot population consisted of individuals all younger than 100 yrs (Fig. 3). The age class distribution at Phortse is slightly unimodal bell shaped with a peak in the 1960s, after which establishment is decreases steadily. The recruitment pattern of *B. utilis* at Dole is sporadic in nature with no single regeneration peak. Similar young age histories of the treeline forming species are reported from other treeline sites in eastern and western parts of the Nepal Himalaya. In spite of differences in plot level comparison, increased recent regeneration of *A. spectabilis* at the treeline ecotone is a common finding of treeline research from the Nepal Himalaya (e.g. at Manang (Ghimire and Lekhak, 2007); Manaslu Conservation Area (Gaire et al., 2014); Langtang National Park (Gaire et al., 2011; Schickhoff et al., 2015; Shrestha et al., 2015); Rolwaling Valley, Gaurishankar Conservation Area (Schickhoff et al., 2015); Makalu-Barun National Park (Chhetri and Cairns, 2015); and the Tibetan side of the Everest region (Lv and Zhang, 2012)).

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treeline at Phortse (f); recent regeneration of *Abies spectabilis* at the lower reaches of the treeline ecotone at Pangboche (g–h). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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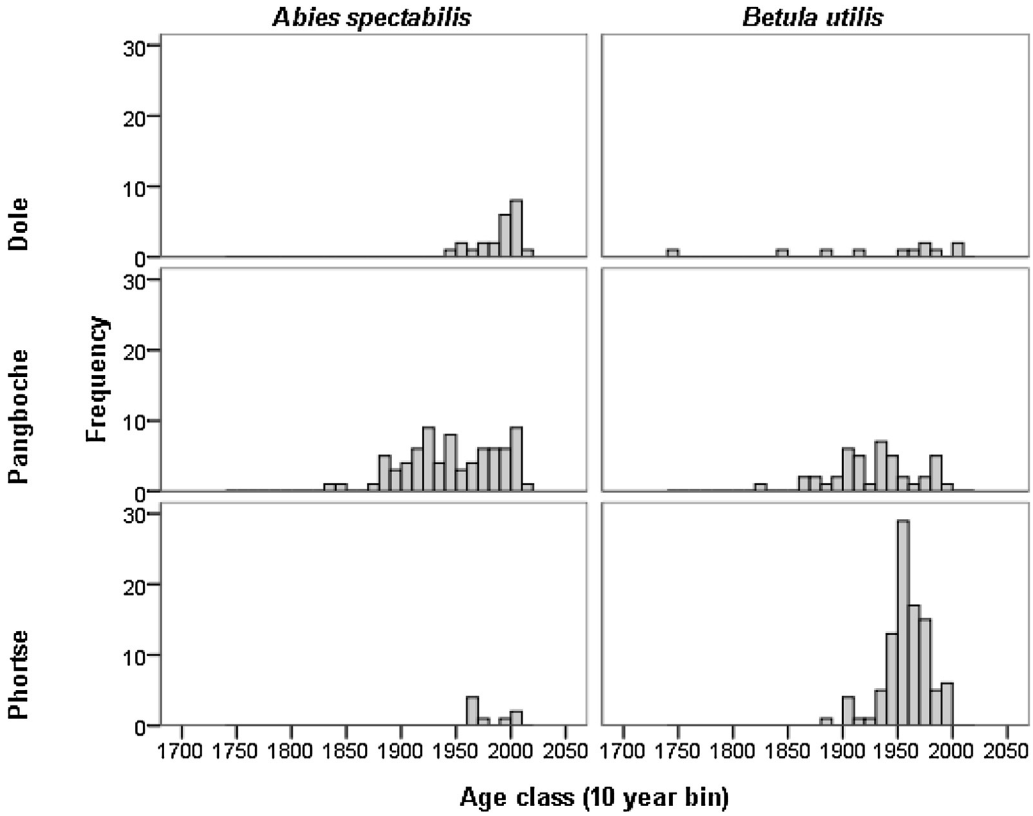

Fig. 3. Age class distribution of *Abies spectabilis* and *Betula utilis* in the treelines of the Sagarmatha National Park, Nepal Himalaya. Here, the normal 10-year age class histograms are first converted into their corresponding calendar year classes, and then shown in calendar years to reveal the temporal distribution of population demography.

3.2. Regeneration and treeline dynamics

B. utilis colonized most plots earlier than *A. spectabilis* (Fig. 4a). At most plots and sites, size parameters (age, diameter and height) decreased with increasing elevation. However, there is evidence of site and species-specific regeneration dynamics (Fig. 4a and b). The Kolmogorov-Smirnov test reveals a significant difference in temporal pattern of recruitment between different sites and species ($\alpha = 0.05$). Similarly, there was a significant difference in intra-site (between species) temporal patterns of recruitment for the majority of sites ($\alpha = 0.05$). Rather poor regeneration of *A. spectabilis* is present in the upper part of most of the treeline sites (except Dole) while the opposite was found moving down towards the timberline (Fig. 4b). Poor regeneration of *B. utilis* in the most recent 20–30 years is prevalent at all sites (Fig. 4b). The presence of seedlings and saplings of *A. spectabilis* in the lower reaches of the plots towards timberline or forest line (Fig. 4b) indicates stand densification and infilling of existing treelines. In the treeline ecotones of the Kalchuman Lake area of Manaslu Conservation Area (Gaire et al., 2014) and in Makalu-Barun National Park (Chhetri and Cairns, 2015), there was a dominance of seedlings and saplings near the timberline rather than the upper treeline. Shrestha et al. (2015), however, found seedlings abundant above the mean treeline in Langtang National Park. Lv and Zhang (2012) found a significant recruitment of *A. spectabilis* in the last three decades and sporadic recruitment in earlier periods in the treeline of the Tibetan side of the Mt. Everest.

Similar to the observations by Gaire et al. (2014) and Shrestha et al. (2007), *B. utilis* formed an abrupt treeline boundary, where tree individuals formed the upper limit instead of seedlings and saplings. We found almost a stable treeline since the second half of the 20th century with a poor recruitment. In contrast to this work, some studies from the treeline of Nepal (Shrestha et al., 2007; Schickhoff et al., 2015) and the Indian Himalaya (Rai et al., 2012) found good regeneration of *B. utilis*, e.g. in the treeline of Rolwaling Valley, Gaurishankar Conservation Area with seedling establishment of *A. spectabilis*, *B. utilis*, and *Sorbus microphylla* extending far above the upper limit of adult trees (Schickhoff et al., 2015).

At most of the studied sites, there were species- and site-specific shifting patterns with little treeline shifting in more recent years (Table 1). The average rate of upward shifting of *A. spectabilis* was 0.93 m/yr and *B. utilis* 0.42 m/yr, with recent stabilization at the majority of sites. Irrespective of plots, the average rate of treeline shifting of *A. spectabilis* at Pangboche since the 1830s was estimated to be 0.7 m/yr with a stagnant position since the 1970s. There is a very dynamic nature of *A. spectabilis* treeline at Dole with the presence of only seedlings and saplings in the D2 (>160 m long) plot and seedlings and saplings above tree individuals in the D1 plot. The upward shifting of the *B. utilis* treeline since the 1830s at Pangboche was 0.38 m/yr with no upward treeline shifting since the 1950s. The upward shifting at Phortse was slightly greater than at Pangboche; the *B. utilis* treeline at Dole has shifted very little over the past ~200 yrs with almost complete stabilization in recent years (Fig. 4 and Table 1).

Treeline shift in response to climate change, though not uniform and universal, is widely observed throughout the world. The shifting observed in the present study is consistent with other studies in the Himalaya, e.g. *P. wallichiana* in western Himalaya, India (Dubey et al., 2003), *A. spectabilis* and *B. utilis* in Manaslu Conservation Area, Nepal (Gaire et al., 2014), *A. spectabilis* in Barun valley, eastern Nepal (Chhetri and Cairns, 2015). During the last six decades, Shrestha et al. (2015) found the *A. spectabilis* treeline in Langtang and Pine treeline in Manang, central Nepal to be stationary. Available investigations, using remote-sensing and repeat photography data, have reported increasing density as well as an upward shifting of the treeline ecotone in Indian Himalaya (Panigrahy et al., 2010; Bharti et al., 2012; Rawat, 2012; Singh et al., 2012, 2013); however, such

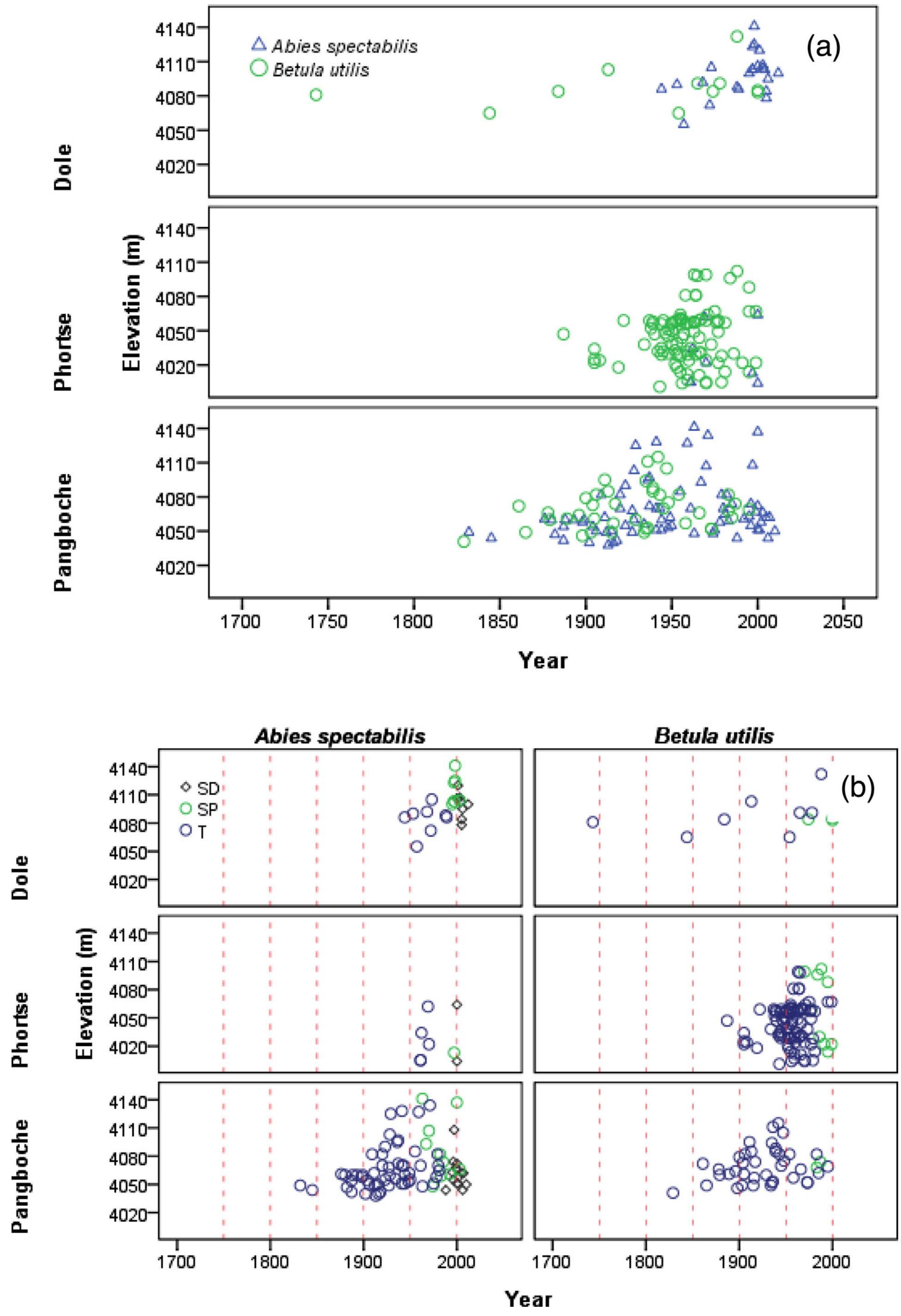

Fig. 4. Sapatio-temporal variation in recruitment and treeline dynamics in Sagarmatha National Park, Nepal Himalaya. Upper panel (4a) provides information about the recruitment history and dynamics of *Abies spectabilis* and *Betula utilis* in the study sites. The lower panel (4b) provides details information on tree, sapling and seedling individuals of the two species with their spatio-temporal distribution and change; SD = Seedling, SP = Sapling, T = Tree.

study is lacking in our area. Schickhoff et al. (2015) and Schwab et al. (2015) reported many species limit of the treeline forming species within a treeline ecotone, indicating complexity in assessing the treeline dynamics. Present field based study, focusing mainly on *A. spectabilis* and *B. utilis* and not considering Krummholz and shrubby *Rhododendron* species, found stable treeline in most of the study sites in recent few decades. Therefore, upward treeline shifting with environmental (climate) change in the Himalayas is not a unidirectional response, but it varies depending upon the climatic history of the area involved, site and species included as well as with scale and approach of the analysis. In spite of shifting until mid-20th century, treelines in Tibet and other mountainous regions in China have shifted very little in recent years (Wang et al., 2006; Liang et al., 2011; Gou et al., 2012; Lv and Zhang, 2012). Several studies from mountain systems in Europe and America have also reported an increase in tree density, and shifting of the treeline to higher elevation or latitude in response to global warming (Camarero and Gutiérrez, 2004; Danby and Hik, 2006; Batllori and Gutiérrez, 2008; Kullman and Öberg, 2009; Harsch et al., 2009; Bogärt et al., 2011;

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Table 1
Treeline or species limit shifting in the treeline ecotones of the Sagarmatha National Park, Nepal Himalaya.

Abies spectabilis							
Sites	Oldest age (yr)	Youngest age (yr)	Oldest position (m)	Youngest position (m)	Age difference (yr)	Elevation difference (m)	Shifting (m/yr)
Pangboche	181	50	4049	4141	131	92	0.70
Phortse	53	14	4005	4064	39	59	1.51
Dole	65	14	4086	4141	51	55	1.08
Average					73.67	68.67	0.93
Betula utilis							
Pangboche	183	70	4072	4115	113	43	0.38
Phortse	126	25	4047	4102	101	55	0.54
Dole	271	126	4081	4132	145	51	0.35
Average					113.67	46.67	0.42

Table 2
Chronology statistics of the residual ring-width chronologies of *Abies spectabilis* and *Betula utilis* in the Sagarmatha National Park, Nepal Himalaya.

Statistics	*Abies spectabilis*	*Betula utilis*
Number of cores (trees)	68 (50)	68 (48)
Chronology span	1838–2012	1831–2012
Mean sensitivity (raw)	0.143	0.29
Mean series length (max)	85 (174)	86 (178)
Mean index (SD)	0.995 (0.12)	0.996 (0.15)
Common period	1932–2007	1940–2007
Number of cores (trees)	42 (34)	35 (22)
Mean sensitivity	0.11	0.15
First-order autocorrelation	0.16	0.05
Mean inter-series correlation	0.29	0.40
Within tree correlation	0.59	0.65
Between tree correlation	0.29	0.40
Express population signal (EPS)	0.94	0.96
Signal-to-noise ratio (SNR)	17.29	23.53
Variance explained (%)	31.7	43
EPS > 85% (no of sample)	14	9

Kirdyanov et al., 2012; Mamet and Kershaw, 2012; Kharuk et al., 2013; Hofgaard et al., 2013; Aakala et al., 2014).

3.3. Tree-ring chronologies

Based on ring-width analysis, ring-width site chronologies (one each) for *A. spectabilis* and *B. utilis* were prepared (Fig. 5). The site chronology of *A. spectabilis* extended from 1838 to 2012, and that for *B. utilis* from 1831 to 2012. The chronology statistics (Table 2) show the dendroclimatic potential of these chronologies (Fritts, 1976; Cook and Kairiukstis, 1990; Speer, 2010). The chronologies of the two species were significantly positively correlated ($r = 0.32–0.37$, $p < 0.05$) during the time span covered by CRU data (1901–2011) as well as for the common period covered by most of the tree-ring series (1940–2007), indicating common climatic signals captured by the chronologies. The chronologies of *A. spectabilis* and *B. utilis* did not show a consistent pattern of growth enhancement in the chronology; rather both fluctuate over time. However, some previous studies have reported consistent tree growth in response to recent climate warming in the Himalayas (e.g. Borgaonkar et al., 2011).

3.4. Climatic response of tree growth and regeneration

Treelines show different structural and physiognomic responses to climate change at different spatio-temporal scales (Holtmeier and Broll, 2005; Holtmeier, 2009; Körner, 2012). The sensitivity and response of the treelines to climate change not only varies with local and regional topographical conditions but also with treeline forms (Holtmeier and Broll, 2005; Harsch and Bader, 2011).

Consistent with global and regional patterns of treelines response, the radial growth of *A. spectabilis* growing in the treelines of SNP is limited mainly by low temperatures during the summer (JJA) growing season. There was a significant positive relationship with the average monthly temperature for August ($p < 0.05$) and the average seasonal temperature of the summer (JJA; $p < 0.05$) months (Fig. 6a). The autumn temperature during the pre-growth year also has a positive relationship with the radial growth. The response with the winter temperature may be linked with the processes like winter embolism, freezing stress, winter desiccation, etc. (Pederson et al., 2004; Fan et al., 2009; Körner, 2012; He et al., 2013). The conifers can have a positive carbon gain on warm winter days when their leaves are not frozen (Pederson et al., 2004). In the absence of adequate snow cover, low winter-season temperatures may cause freezing injury and fine roots mortality due to frost penetration, while a deep snow pack in late winter can reduce radial growth rates by maintaining low soil temperatures and delaying initiation of cambial expansion (Pederson et al., 2004; He et al., 2013). Correlations between climate and growth of *A. spectabilis* near the treeline in western (Sano et al., 2005) and central Nepal (Gaire et al., 2011; Kharal et al., 2014) were negative with spring season (MAM) temperature and positive with the same month's precipitation. Climate systems in the western part of Nepal differ slightly from those in the eastern part and may account for variations in response. Yadav et al. (2004) not only reported significantly negative correlations between ring width chronologies of *A. spectabilis* from treelines in Himachal Pradesh and Uttarakhand, India and long-term pre-monsoon temperature but also a weakening temperature signal in recent years.

In spite of significant positive correlation between the ring-width chronologies of the two species, their climatic response in month-to-month comparison differs (Fig. 6a and b). Differences in temperature and moisture sensitivity between the conifer and broad-leaved tree species may be associated with their contrasting phenology and physiological traits (Pederson et al., 2004; Körner, 2012). The correlation function analysis revealed that there was a significant positive relationship ($p < 0.05$) between the radial growth of *B. utilis* and monthly precipitation during the previous October, current March and May, and with spring season (MAM) precipitation, while a significant ($p < 0.05$) negative relationship with temperature exists for the same season (Fig. 6b). This indicates that radial growth of *B. utilis* at the treeline of SNP was mainly limited by temperature induced moisture stress during the spring season. During spring, temperature increases rapidly and precipitation becomes insufficient to meet evapotranspiration demand. The response we obtained is consistent with other studies carried out in treeline-forming *Betula* species (Bräuning, 2004 Takahashi et al., 2005; Bhattacharyya et al., 2006; Dawadi et al., 2013; Wang et al., 2013; Liang et al., 2014). Reduced pre-monsoon moisture availability is a primary growth-limiting factor for *B. utilis* at many timberline sites (Sagarmatha, Langtang and Manaslu) of the Nepal Himalaya with a high percentage of missing rings or narrow rings coinciding with years that are dry and warm in the pre-monsoon

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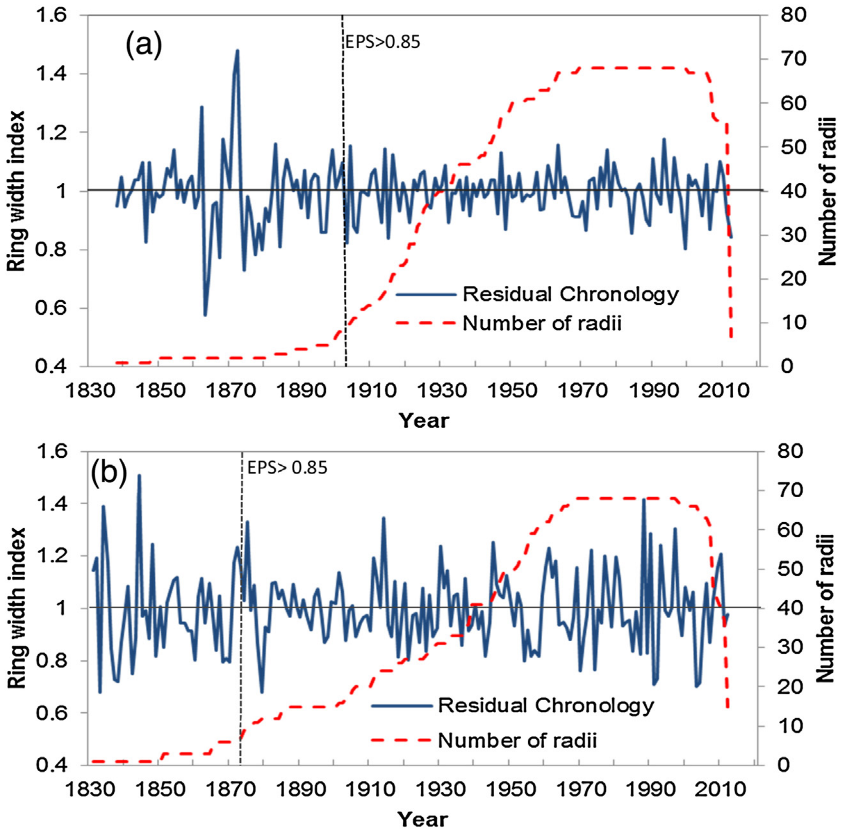

Fig. 5. Tree ring-width residual site chronologies of *Abies spectabilis* (a) and *Betula utilis* (b) from the treelines of the Sagarmatha National Park, Nepal Himalaya. In the figures sample depth (Red dashed line) and year crossing the EPS threshold level (Black dashed line) are also shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

season (Liang et al., 2014). Bhattacharyya et al. (2006) reported that higher temperatures and less rainfall during pre-monsoon months result in lower tree growth of *B. utilis*.

The growth response of treeline-forming trees to climate change in the Himalaya is spatiotemporally different, and species-specific (Bhattacharyya and Chaudhary, 2003; Yadav et al., 2004; Sano et al., 2005; Bhattacharyya et al., 2006; Gaire et al., 2011, 2014; Lv and Zhang, 2012; Dawadi et al., 2013; Liang et al., 2014). Studies also report that radial growth of treeline conifers is more responsive to temperature than precipitation (Bräuning, 2004; Sano et al., 2005; Bhattacharyya and Shah, 2009; Borgaonkar et al., 2011; Gaire et al., 2011, 2014; Schickhoff et al., 2015).

In treeline ecotones, the climate conditions that facilitate radial growth may be similar to those conducive to recruitment (Dang et al., 2009; Lv and Zhang, 2012; Zhao et al., 2013), or the processes of recruitment and growth may respond differently to climatic factors (Daniels and Veblen, 2004; Wang et al., 2006). In the present study, the climatic factor that limits or favor radial growth of *A. spectabilis* and *B. utilis* were not perfectly same as that for regeneration of the same species, however, differences exist in month-to-month comparisons and site-to-site comparisons (Figs. 6 and 7). The different details in the response among the sites may be associated with the influence of local topographic conditions and/or tree age (Carrer and Urbinati, 2004; Wang et al., 2009; Mérian and Lebourgeois, 2011).

The regeneration-climate relationship is species-specific as well as site dependent (Fig. 7). The regeneration of *A. spectabilis* was favored by high temperatures in both winter and summer provided there was no moisture limitation. There is a significant positive relationship ($p < 0.01–0.05$) between the regeneration of *A. spectabilis* at Pangboche and monthly average temperature in most of the months and monthly precipitation in March (Fig. 7a). An almost identical response was obtained between the regeneration of *A. spectabilis* at Dole-Phortse and climate (Fig. 7b). However, month-to-month comparisons exhibit some variations in response between sites that may be associated with variations in topography and other feedback mechanisms. Studies have reported the sensitivity of *Abies* recruitments with temperature, moisture, and/or drought conditions (Liang et al., 2011; Lv and Zhang, 2012; Gaire et al., 2014). *A. spectabilis* recruitment was positively correlated with monthly mean air temperature in June and September and with Palmer Drought Severity Index (PDSI) in June at timberline on the Tibetan side of the Everest region (Lv and Zhang, 2012). In the treelines of the Manaslu region, central Nepal, regeneration of *A. spectabilis* is favored by high temperature throughout the year together with sufficient moisture during the summer season (Gaire et al., 2014). Consistent with our study (Fig. 7a and b), *A. georgei* var. *smithii* recruitment in a treeline on the southeastern Tibetan Plateau was sensitive to both summer and winter temperatures with a significant positive correlation (Liang et al., 2011). From a transplant experiment in a treeline ecotone in SE Tibet, Shen et al. (2014) demonstrated that early growing-season freezing events determine the annual mortality of *A. georgei* seedlings above the treeline.

The regeneration-climate relationship of *B. utilis* is spatiotemporally differentiated (Fig. 7c–f). Up until 1990s to which time establishment of *B. utilis* was found, high average monthly temperatures and precipitation during the summer and autumn months favored the regeneration at Pangboche, with a significant positive relationship ($p < 0.05$) between regeneration and monthly mean temperatures of July to October (Fig. 7d). The lack of recently established seedlings and saplings of *B. utilis* in treelines weak-

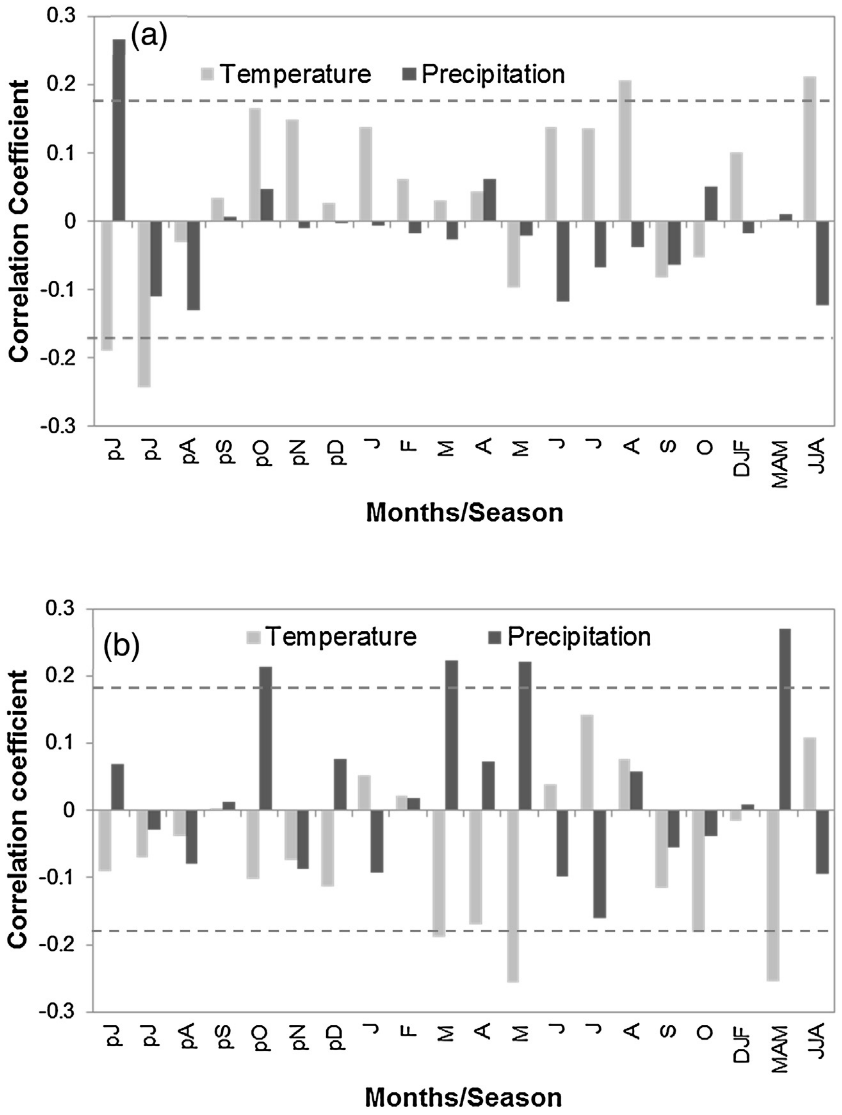

Fig. 6. Correlation (Pearson's correlation) between radial growth (Ring width residual chronology) of *Abies spectabilis* and *Betula utilis* and monthly climate data in the study area of the Sagarmatha National Park, Nepal Himalaya. The horizontal dashed line indicates the 95% significant threshold. The pJ to pD indicates June to December of the previous year and J to O indicates months of current year starting from January and ending at October; DJF, MAM and JJA represents the seasonal average climate of winter (December to February), spring (March to May) and summer (June to August), respectively.

ens the relationship with climate parameters when we consider the entire period covered by CRU climatic data (1901–2011). In contrast to Pangboche, the regeneration at Dole was negatively influenced ($p < 0.05$) by high monthly mean temperatures in July. In the study area, there is a consistent increasing of temperature and weakening of precipitation, with high intra-annual variability (Salerno et al., 2015). In spite of the warmer climate, moisture stress due to weakening precipitation might limit new seedling and sapling establishment. Schickhoff et al. (2015) found significant positive correlations of seedling and sapling abundance with soil moisture for *A. spectabilis*, *B. utilis*, and *R. campanulatum*, and with soil temperature for *A. spectabilis*, *B. utilis*, and *Sorbus*. Some of the spatial difference and weak regeneration-climate response of *B. utilis* may be explained by temporal changes in sensitivity, uncertainties in age estimation using regression models, or influences of non-climatic abiotic and biotic factors on regeneration of birch seedlings.

In common with worldwide responses (Körner and Paulsen, 2004; Körner, 2012), temperature is the dominant climatic factors controlling regeneration, growth and dynamics in the studied treelines in the SNP region. Sustained and favorable climatic conditions during establishment, and particularly during recruitment, are crucial for controlling treeline dynamics (Wang et al., 2006; Mamet and Kershaw, 2012) as one poor year is sufficient to kill regeneration established over many favorable years. However, warming temperatures may not necessarily lead to unidirectional changes in treeline position as the direct influence of temperature may be countered by interactions with other factors such as precipitation, cold-induced photo-inhibition, disturbance, or plant–plant interactions (Bekker, 2005; Danby and Hik, 2007; Munier et al., 2012; Speed et al., 2011; Körner, 2012; Schickhoff et al., 2015). In comparison to *B. utilis*, growth and regeneration of *A. spectabilis* is more sensitive to temperature than precipitation. The high regeneration of seedlings and saplings of *A. spectabilis* in the lower reaches of the treeline towards the timberline can be explained by the significant positive relationship between regeneration and climate. We found very few seedlings and saplings of *A. spectabilis* and *B. utilis* in the upper reaches of the plots near the tree species limits with recently stabilized treeline position of *A. spectabilis* at two sites and *B. utilis* at all sites. Lack of seed dispersal is not limiting for recent treeline

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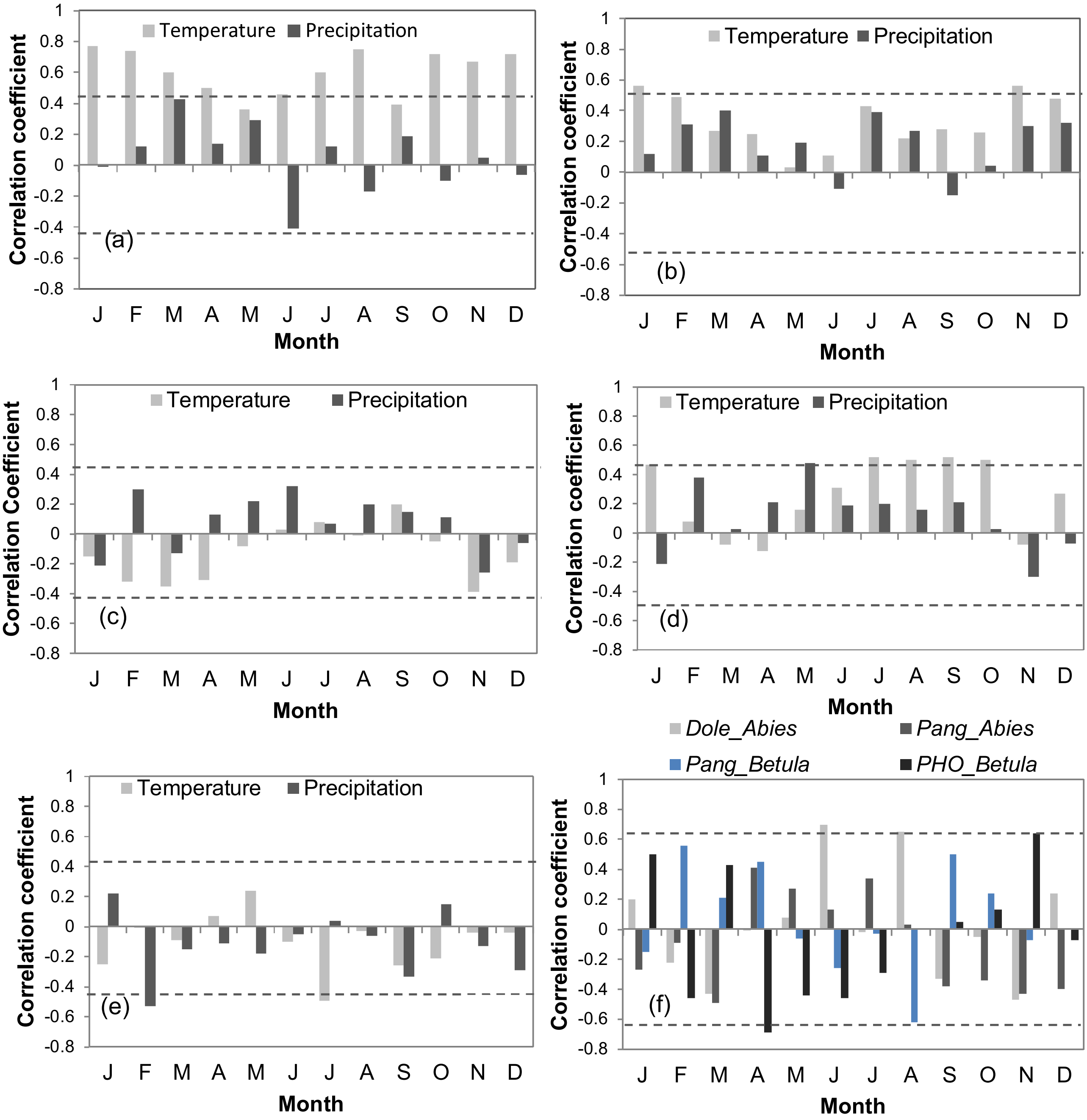

Fig. 7. Pearson's correlation between regeneration of *Abies spectabilis* and *Betula utilis* and monthly climate data in the treelines of the Sagarmatha National Park, Nepal Himalaya. The horizontal dashed line indicates the 95% significant threshold. Correlation between CRU climate data and regeneration of *A. spectabilis* at the treelines at Pangboche (a) and Dole-Phortse (b); correlation between CRU climate data and regeneration of *B. utilis* at the treelines at Pangboche for different periods: 1901–2011 (c) and 1901–1990 (d) and at Phortse (e); relationship between regeneration of both the species with Chaurikharka station precipitation data (f).

shifts; some seedlings and saplings were found to be growing up to several meters above the tree individuals in the present study and in other treeline areas of Nepal Himalaya (Gaire et al., 2011, 2014; Schickhoff et al., 2015; Shrestha et al., 2015).

The regions at and above the treeline are commonly used as summer grazing area in the Himalaya. In addition to weakening precipitation with increasing interannual variability, non-climatic factors such as micro-topography, the competition with dense Krummholz *Rhododendron* trees and shrubs, herbivory, and the competitive ability of treeline forming species might be moderating the beneficial impacts of temperature warming, and ultimately controlling recent seedling establishment and treeline shift (Shrestha et al., 2007, 2015; Munier et al., 2012; Rai et al., 2012; Wang et al., 2012; Zhao et al., 2013; Chhetri and Cairns, 2015; Schickhoff et al., 2015; Schwab et al., 2015). Shrestha et al. (2007) observed that there was a lack of treeline shift of *B. utilis* in *trans*-Himalaya, Manang due to anthropogenic pressure. Shrestha et al. (2015) suggested that the stationary *A. spectabilis* treeline, even given warming temperatures in the Langtang area, is regulated by non-climatic factors, particularly grazing. Schickhoff et al. (2015) found a negative correlation between the abundance and density of *R. campanulatum* and the recruitment of other tree species, due to competition with the dense foliage of evergreen Rhododendron as well as a probable allelopathic effect. In spite of favorable cli-

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mate, the dense Krummholz belt can be an effective barrier for upslope migration of other tree species (Schickhoff et al., 2015; Schwab et al., 2015).

Liang et al. (2014) concluded that birch (*B. utilis*) treelines of Himalayas are drought-induced alpine timberlines and that this species is increasingly at risk of survival. We are skeptical of this conclusion. We argue that their categorization of birch treelines was hasty as they mainly sampled at dry sites and did not consider the population demography of the species. Though moisture stress during the spring season affects growth, we (field observation by NP Gaire) found a large number of recently recruiting *B. utilis* seedlings and saplings above the tree individuals in the treelines of Kanchenjunga Conservation Area, eastern Nepal and fair regeneration at the timberline at other sites in mid- and far-western Nepal. These areas have been experiencing an increasing trend in average annual temperature but no significant trend in annual precipitation with some stations depicting slightly increasing while some decreasing pattern. Comparing with findings of several studies and considering discrepancies in the results, we propose further comprehensive study incorporating, in addition to climatic factors, grazing inclusion-exclusion and transplantation experiments, masting in seed production, testing of growth or carbon limitation in treeline formation for better understanding of the response of treelines and their dynamics to climate change.

4. Conclusions

We assessed treeline dynamics during the past ∼200 years in the Sagarmatha National Park, in eastern Nepal Himalaya. The study found the existence of heterogeneous regeneration and treeline dynamics with recent stable treeline position at most sites. Broadly, warm temperature during the growing season together with sufficient moisture favored the growth of *A. spectabilis* while moisture stress during the spring season limited the growth of *B. utilis*. The climatic response of regeneration in the treelines was species-specific as well as site dependent. High winter and summer temperatures favored regeneration of *A. spectabilis* while the relationship between climatic parameters and regeneration in case of *B. utilis* was spatio-temporally unstable. In spite of a warming climate, we found poor recent regeneration in the upper reaches of the treeline ecotone. This indicates that along with favorable climate, site dependent abiotic factors, age dependent species-specific competitive abilities with Krummholz and dwarf scrub belts during the recruitment phase, and intensity of grazing will determine future treeline dynamics in the region.

Acknowledgements

NP Gaire is grantee of NAST PhD fellowship. Authors are thankful to Department of National Park and Wildlife Conservation, Kathmandu for the permission to conduct this study in SNP. We are thankful to Prabina Rana, Mahesh Adhikari, Arjun KC from NAST/TU, the SNP staff at Namche, and local guides for their support during fieldwork. Prof. James H Speer, Indiana State University, USA helped improve the manuscript and provided with critical comments. Dr Kirsti Ashworth, University of Michigan, USA kindly edited the languages in the revised manuscript. Uday Thapa from the University of Minnesota, USA helped prepare the location map and provided useful feedbacks. EvK2CNR, Italy provided partial financial support for the fieldwork. We are thankful to two anonymous reviewers for their constructive and appreciative comments on earlier version of the manuscript.

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Please cite this article in press as: Gaire, N.P., et al., Site- and species-specific treeline responses to climatic variability in eastern Nepal Himalaya. Dendrochronologia (2016), http://dx.doi.org/10.1016/j.dendro.2016.03.001

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Please cite this article in press as: Gaire, N.P., et al., Site- and species-specific treeline responses to climatic variability in eastern Nepal Himalaya. Dendrochronologia (2016), http://dx.doi.org/10.1016/j.dendro.2016.03.001