FACTORS STRUCTURING TREELINE DYNAMICS OF THE NEPAL HIMALAYA

A Dissertation

by

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ABSTRACT

The alpine treeline ecotone is an important component of mountain ecosystems of the Nepal Himalayas; it plays a vital role in the livelihood of indigenous people and provides ecosystem services. However, the region faces a problem of paucity of data on treeline characteristics at the regional, landscape, and local scales. Therefore, I applied remote sensing and geographic information science approaches to investigate the treeline ecotone at the regional (entire Nepal) and landscape (Barun and Manang Valleys) scales. Treeline elevation ranges from 3300–4300 m. *Abies spectabilis*, *Betula utilis*, and *Pinus wallichiana* are the main treeline-forming species in the Nepal Himalayas. There is an east to west treeline elevation gradient at the regional scale. No slope exposure is observed at the regional scale; however, at the landscape scale, slope exposure is present only in a disturbed area. From the landscape scale study, I found that topography and human disturbance are the main treeline-controlling factors in Barun and Manang, respectively. Diverse treeline-forming species and treeline nature observed in the landscape and regional scale study suggested more investigation was needed at the local scale. Therefore, I established two transects of 20 m width and 120 m length (100 m above and 20 m below the forestline) in the *Betula utilis* sub-alpine forest of the Dhorpatan Hunting Reserve in western Nepal to understand the local scale treeline dynamics. Poor regeneration was observed above the forestline in both transects compared to below the forestline. Low regeneration at the treeline ecotone suggested site-specific biotic and abiotic controlling factors. Seedling and sapling establishment above the forestline is limited by a lack of moisture, an absence of suitable microsites, and the presence of herbivores. I found the treeline stable at the local scale. I used the Maxent species distribution modeling approach to predict the likelihood of treeline advance in the Nepal Himalayas by modeling the habitat suitability of three dominant treeline species—*A. spectabilis*, *B. utilis*, and *P. wallichiana*—under present and alternative future climates. Temperature-related climatic variables and elevation explained the greatest amount of variance in the distribution of the study species. Under future climate models, I found a regional increase in habitat suitability of all three treeline species that predicted a potential for northward and upslope advance.

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NOMENCLATURE

ACA	Annapurna Conservation Area
ALOS	Advance Land Observing Satellite
ANOVA	Analysis of Variance
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
ATCOR	Atmospheric Correction for Flat Terrain
BASE	Bielefeld Academic Search Engine
BCC	Beijing Climate Center
CCAFS	Climate Change, Agriculture and Food Security
CGIAR	Consultative Group on International Agriculture Research
CMIP	Coupled Model Intercomparison Project
DBH	Diameter at Breast Height
DEM	Digital Elevation Model
DHR	Dhorpatan Hunting Reserve
ESA	European Space Agency
FLAASH	Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes
GBIF	Global Biodiversity Information Facility
GCAOGC	Global Coupled Atmosphere-Ocean General Circulation Model
GCM	General Circulation Model
GIS	Geographic Information Science

GSM	Global Climate Models
ICIMOD	International Center for Integrated Mountain Development
IPCC	International Panel on Cliamte Change
IRS	Indian Remote Sensing Satellites
LiDAR	Light Detection and Ranging
Maxent	Maximum Entropy
MBNP	Makalu Barun National Park
MODIS	Moderate-resolution Imaging Spectroradiometer
MSS	Multispectral Scanner
NDVI	Normalized Difference Vegetation Index
RADER	RAdio Detection And Ranging
RCP	Representative Carbon Pathway
RRI	Relative Radiation Index
RS	Remote Sensing
SAR	Synthetic Aperture Radar
SDM	Species Distribution Modeling
SII	Solar Illumination Index
SPOT	Satellite Pour l’Observation de la Terre
SRTM	Shuttle Radar Topography Mission
TM	Thematic Mapper
TPI	Topographic Position Index
UAV	Unmanned Aerial Vehicles

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CHAPTER I

INTRODUCTION

TREELINE ECOTONE

The treeline ecotone is the high-elevation limit of forests, commonly referred to as *treeline*, *timberline*, or *forestline*, and represents transitional vegetation zones between the closed continuous forest below and the treeless alpine zone above (Paulsen et al., 2000; Körner, 2012; Singh et al., 2012). In the world, treeline elevations range from near sea level, as in northern Canada and Alaska, up to 4700 m above sea level (all elevations in this study are above sea level) in Tibet and 5000 m in the Andes of Bolivia and Chile (Troll, 1973). Evergreen pinaceae species such as spruce (*Picea*), fir (*Abies*), and pine (*Pinus*); other conifers such as hemlock (*Tsuga*), juniper (*Juniperus*), and cypress (*Chamaecyparis*); and angiosperms such as birch (*Betula*) are the most common treeline-forming species around the world (Jobbagy and Jackson, 2000; Richardson and Friedland, 2009). The scientific study of treelines began in the Swiss Alps during the 16th and 17th centuries (Richardson and Friedland, 2009), and since then many studies have been carried out around the world. The special ecological structure and function of the treeline ecotone make it a sensitive indicator of global change and a focus of current research (Zhang et al., 2001). It is now almost an unequivocal and common concern that climate warming will facilitate changes in tree physiognomy, and increased recruitment and establishment coupled with increased density within the ecotone and beyond species limit will lead to an upward movement of the treeline (Körner, 2012). Dendroecological studies have documented the altitudinal expansion of the treeline ecotone in many mountain ranges of the world, including the Green Mountains, United States (Beckage et al., 2008); the Polar Urals, Russia (Devi et al., 2008); and the central Swiss Alps, Switzerland (Vittoz et al., 2008). Meanwhile, several other studies in the Western Mountains, New Zealand (Cullen et al., 2001); the Glacier National Park, United States (Klasner and Fagre, 2002); the Central Tianshan Mountains, China (Wang et al., 2006); and the Tibetan plateau (Liang et al., 2011) showed no change in the location of the treeline ecotone. In a meta-analysis of a global data set of 166 treeline sites, Harsch et al. (2009) showed treeline advance at 52% of sites since 1900, stability in 47% sites, and treeline recession in only 1% of the sites. These disparate findings imply that the spatiotemporal variations in site-specific and species-specific treeline phenomena are important study subjects in relation to global, regional, or local environmental changes.

Most of the studies carried out so far are from North America and Europe, and the Himalayan region is still underrepresented. Several researchers (Chhetri et al., 2017; Holtmeier, 2009; Schickhoff, 2005; Shi and Wu, 2012) have noticed the variety of treeline structure and growth forms in the Himalayas and indicated that little is known about the spatial distribution of the treeline ecotone and its relation to climate and topography. Covering an understudied area like the Himalayas will help to answer the broad ecological question of treeline formation worldwide. Descriptions of treeline position, structure, pattern, and dynamics in the Himalayas will provide insights into the ecological and biogeographical processes and relationships between the treeline ecotone and climate conditions, the mechanisms of treeline formation, and the responses of tree growth and regeneration to climate change (Shi and Wu, 2013).

Himalayan treeline ecotone

Himalayan treeline ecotones show considerable differences in altitudinal position as well as in physiognomy and species composition (Chhetri et al., 2017; Schickhoff, 2005). The Himalayan region is considered to be a sensitive global climate change (Mishra and Mainali, 2017; Xu et al., 2009), and it is believed that the treeline will move upward in response to global change, particularly global warming. Upward movement of the treeline and encroachment of woody vegetation on alpine meadows are widely reported (Beckage et al., 2008; Vittoz et al., 2008); however, few studies have been carried out in the Himalayas. In fact, research on timberline ecological conditions in the Himalayas is still in its infancy (Chhetri and Shrestha, 2009; Schickhoff, 2005).

In the eastern Himalayas, researchers estimated that the treeline has shifted upwards by 110 m over the past century (Xu et al., 2009). A study of repeated photography carried out by Baker and Moseley (2007) indicated that the current timberline on Baima Snow Mountain, China, has moved 67 m in elevation and a distance of 270 m upslope from its 1923 location. Similarly, in the Himanchal Pradesh, Western Himalayas, Dubey et al. (2003) recorded an upwards shift of treeline species by 19 m and 14 m over 10-year periods on the south and north slopes, respectively. Likewise, Panigrahy et al. (2010) recorded an apparent shift on Nanda Devi Biosphere

Reserve in the Central Himalayas of around 300 m in timberline since 1960 using topographic maps and satellite imagery. Alternatively, a study carried out by Liang et al. (2011) in the Tibetan Plateau highlighted the impact of global warming on the increased population density of the Smith fir (*Abies georgei*) rather than the upwards shift of treeline position. Additionally, in remote-sensing-based observations on treeline changes in Uttarakhand, India, Singh et al. (2012) mentioned upward shifting of vegetation; however, a study by Bharti et al. (2012) based on remote-sensing analysis of Landsat imagery indicated that there has been no geographical shift in the upper limit of treeline in the Nanda Devi Biosphere Reserve (Uttarakhand), India. Thus, studies have revealed a variety of treeline structure and growth forms in the Himalayas. The unique environment in the Himalayas—with complex mosaics of anthropogenic, topographic, and climatic influences in treeline phenomena—offers many opportunities for discovering insights into the ecological and biogeographical processes of treeline formation.

Treeline in Nepal

In the Nepal Himalayas, variations in treeline elevations follow particular Himalayan patterns. The position of the treeline varies between approximately 3600–4500 m and varies between the eastern, central, and western regions (Schickhoff, 2005), with the pattern of monsoon rains playing a role (Stainton, 1972). The treeline elevation of Eastern Nepal is generally higher than in Western Nepal. For example, the treeline in

Eastern Nepal reaches a maximum elevation of 4110 m, the treeline in Central Nepal varies from 3048–3962 m, and the treeline in Western Nepal reaches up to 3048 m (Manandhar, 2002). In the case of the Nepal Himalayas, *Abies spectabilis* (Humla, Jumla, Mugu; mainly in Central Nepal—Annapurna region, Manasalu region, Langtang region; Everest region, Kanchenjunga region, Makalu Barun region [Figure 1-1]), *Pinus wallichiana* (extensive stands in Western Nepal—Humla Jumla region; Manang Valley, Manasalu area, etc.), *Betula utilis* (Manang Valley, Langtang Valley, Khumbu region), *Larix griffithiana*, *Rhododendron companulatum*, *Sorbus microphylla*, and *Juniperus indica* are the treeline species. In Nepal, few extensive scientific study has been carried out on the treeline area, but in recent years, there has been an increased interest in treeline research (Chhetri and Cairns, 2015; Gaire et al., 2014; Shrestha et al., 2014; Suwal et al., 2016) triggered by concerns about the climate change and potential shift in the high mountain vegetation zone. So far, dendrochronological and dendroecological studies on the treelines of Nepal have depicted some site- and species-specific treeline dynamics and influences of climatic and non-climatic factors in the ecotone. However, a proper investigation into the causes of treeline shift was necessary in order to more fully understand the treeline dynamics in the Nepal Himalayas.

Figure 1-1: *Abies spectabilis* treeline from Barun Valley, Eastern Nepal.

In the Nepal Himalayas, there is still a lack of consistent data on treeline position, nature, and dynamics at the landscape and plot scales. The treeline ecotone of the Nepal Himalayas is characterized by contrasting climatic, orographic, and anthropogenic conditions (Chhetri et al., 2017; Schickhoff, 2005). For this study, the roles of geomorphic processes and patterns and human disturbance in shaping the spatial structure of the treeline ecotone needed to be investigated along with climatic factors. Mapping of the treeline ecotone at the landscape scale help to detect both the current and historical position of the treeline ecotone. It also help to differentiate the climatic, anthropogenic, and topographic treeline. Remote sensing (RS) and geographic information science (GIS) approaches were utilized to know the treeline dynamics at the landscape scale, and a field-based dendroecological study was utilized to acquire a more comprehensive view of the treeline ecotone dynamics at the plot scale. Studies emphasized in the plot scale study helped to understand the change in age structure, recruitment pattern, and biological response of individual trees. By combining the landscape scale (RS and GIS approaches) and plot scale (dendroecological approach), I was able to minimize the risk of over- or underestimating potential treeline advance (Mathisen et al., 2013). Therefore, a combination of a landscape-based RS and GIS and plot-based dendroecological study was used to investigate cross-scale interaction at the treeline ecotone.

RESEARCH QUESTIONS AND OBJECTIVES

In the Himalaya region, this type of cross-scale treeline study had not been carried out before; therefore, this comprehensive study combined coarse- and fine- scale techniques to address the following research questions:

1. What are the treeline positions, the species compositions, and the spatial patterns?
2. What kind of structural changes have occurred in the treeline ecotone?

3. How will the habitat suitability of treeline species change in future climate change scenarios?

The objectives of this study were:

1. Map the present treeline and forestline position and identify the species composition of the treeline.
2. Determine the recruitment pattern below and above the treeline.
3. Investigate how the treeline will respond to future climate-change scenarios.

STUDY AREA

Nepal (26°22′, 30°27′ N and 80°04′, 88°12′ E) is a mountainous country and occupies the central part of the Himalayas. The east-west distance across Nepal is approximately 1000 km, the north-south extent is approximately 200 km, covering 147490 km^2 nationally. The elevation of Nepal ranges from 60 m in the south to over 8500 m in the north (Figure 1-2). This huge variation in elevation contribute in a complex topography and diverse climate. Nepal is primarily influenced by the South Asian monsoon in summer and by westerly winds in the winter. Nepal receives more than 80 % of its total precipitation from the summer monsoon, and precipitation varies along an east-to-west gradient. This variation in climate and topography results in diverse vegetation zones ranging from tropical to alpine (Chhetri et al., 2017).

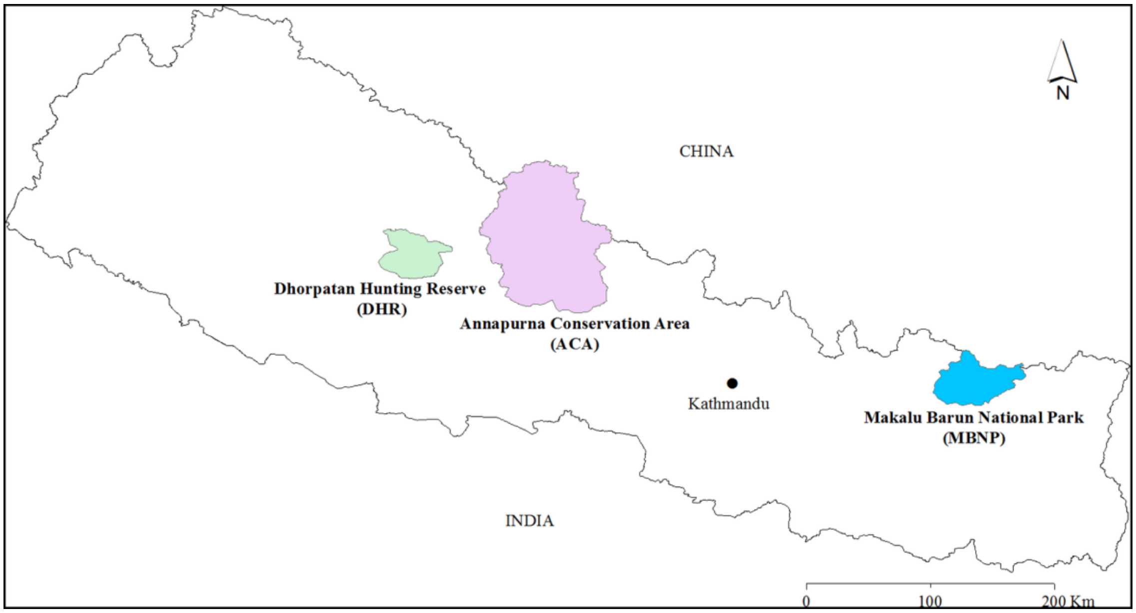

Figure 1-2: Location of study sites. Makalu Barun National Park (MBNP) and Annapurna Conservation Area (ACA) were the sites for the landscape scale study. Dhorpatan Hunting Reserve (DHR) was the site for the local scale study.

Altitudinal position and species composition of the treeline ecotone varies considerably in the Himalaya region (Schickhoff, 2005). Treeline position and factors structuring the treeline ecotone in different parts of Nepal are unknown. In this study, I have select three study sites to represent the Eastern, Central and Western part of Nepal (Figure 1-2) to map the existing treeline position and investigate the factors structuring the treeline ecotone position and dynamics. I will adopt three spatial scale study, first at regional scale to identify the main treeline forming species of the Nepal and how their potential distribution could change in climate change scenarios, second at landscape sale to differential treeline into climatic, topographic, and anthropogenic types, and third at plot scale to reconstruct the historic treeline and to see the current recruitment pattern. I have selected Makalu Barun National Park, Eastern Nepal, and Annapurna Conservation Area, Central Nepal for landscape scale study. I selected Dhorpatan Hunting Reserve, Western Nepal for local scale study.

Makalu Barun National Park, Eastern Nepal

Makalu Barun National Park (MBNP), Eastern Nepal (Figure 1-2) was established in 1992 and covers an area of 1500 km^2. This study was focused on U-shaped Barun Valley in the northern part of the park where upper limit of forest is present. This stream is glacially-fed streams and shows evidence of the Pleistocene glaciation at the altitude belt with sub-alpine forests today (Carpenter and Zomer, 1996). MBNP lies within the subtropical Asian monsoon zone, characterized by a pronounced summer rainfall falling between June and September. *Abies spectabilis* (Himalayan silver fir) is a treeline species and covers the south-, north- and east-facing slopes, and treeline ecotone elevation range from 3800–4100 m. There is no cattle grazing and timber harvesting in the treeline ecotone area, and therefore it can be considered as an undisturbed site.

Annapurna Conservation Area, Central Nepal

Annapurna Conservation Area (ACA), Central Nepal was established in 1985, and it is a largest protected area of Nepal. Manang Valley of ACA was selected for this research

(Figure 1-2). Manang Valley is a part of the trans-Himalayan arid region of Nepal that lies between the Tibetan plateau to the north and the main Himalayan axis to the south (Annapurna range). The valley is surrounded by many mountain ridges and steep slopes, and climate is characterized by warm dry summers with frequent strong winds, which produce xeric conditions. Treeline ecotone range from 3800–4100 m and *Pinus wallichiana* (Blue pine), *Betula utilis* (Bhojpatra), and *A. spectabilis* are the treeline species. Local people use the treeline ecotone area as pastures, so this area is suitable to investigate how agropastoralism interacts with the treeline ecotone dynamics.

Dhorpatan Hunting Reserve, Western Nepal

Dhorpatan Hunting Reserve (DHR), Western Nepal was established in 1983 and gazetted in 1987, it covers the area of 1325 km^2 and elevation range from 2000–7246 m. DHR covers 26.42% of Baglung, 14.13% of Myagdi, and 59.45% of Rukum districts of Nepal (Karki and Thapa, 2007). Climate of the DHR varies from sub-tropical in the lower elevation to alpine climate in the higher elevation zone. Average annual temperature of the reserve is 6.3°C and receives annual precipitation >1000 mm. Long term CRU climate data indicated increasing temperature trend and decreasing precipitation trend for the region. Common flora of the reserve are *Abies spectabilis* (Silver Fir), *Betula utilis* (Birch), *Pinus wallichiana* (Blue pine), *Quercus semecarpifolia* (Oak), *Rhododendron arboretum,* and *Rhododendron campanulatum* (Rhododendrons). Common fauna are *Pseudois nayaur* (Blue Sheep), *Nemorhaedus goral* (Goral), *Hemitragus jemlahicus* (Himalayan tahr), and *Moschus chrysogaster* (Himalayan musk deer). Ground is covered with moss and litter. *Betula utilis* is a dominant tree species in treeline ecotone of DHR. Buki grass (*Carex sp*.), *R. anthropogen* and *Cassiope fastigiata* are the dominant species above the treeline.

DISSERTATION CHAPTERS OUTLINE

This dissertation includes four main chapters.

Chapter 2: I reviewed more than 100 treeline studies that applied RS and GIS techniques. This chapter describes how and when researchers started to use RS and GIS in their treeline-related studies. In addition, the chapter describes the various types of satellite and RS images, techniques, and methods used in treeline studies.

Chapter 3: This chapter depicts the results obtained from RS- and GIS-based treeline mapping at the regional and landscape scales. The chapter describes the species composition, current treeline positions, slope exposure effect, and treeline type of the Nepal Himalayas. This chapter essentially addresses three main research questions: (1) What are the species composition and spatial pattern of treelines? and (2) How and why do treelines differ across different locations? To address these research questions, I mapped and analyzed the treeline at the regional scale by covering all of Nepal, and at the landscape scale by focusing on Barun and Manang Valleys.

Chapter 4: This chapter describes the results from the study of two transects of 20 m width and 120 m length (100 m above and 20 m below the forestline) in the *Betula* *utilis* sub-alpine forest of DHR in Western Nepal. I address the following research questions in this chapter: (1) How do rising temperatures influence recruitment at the treeline ecotone? and (2) Is the availability of suitable regeneration microsites an important factor in limiting establishment above the forestline? In the study, this analysis was performed by comparing age structure and recruitment above and below the forestline and by analyzing the spatial patterns of individual establishment.

Chapter 5: The response of treeline-forming species to global climate change is uncertain. Therefore, in this chapter, I discuss how I used the Maxent species distribution modeling software to predict the likelihood of treeline advance in the Nepalese Himalayas by modeling the habitat suitability of three dominant treeline species—*Abies spectabilis*, *Betula utilis*, and *Pinus wallichiana*—under present and alternative future climates. I present the result of species distribution modeling that I used to determine if the distributions of three common Himalayan treeline-forming species are defined by climate and predict if their ranges are likely to expand or contract under alternative climatic regimes through an increase or decrease in suitable habitat.

CHAPTER II

REMOTE SENSING AND GEOGRAPHIC INFORMATION SCIENCE TECHNIQUES IN STUDIES ON TREELINE ECOTONE DYNAMICS

INTRODUCTION

Ecotones are areas between two biomes, thus comprising heterogeneous landscapes with vegetation patches of varying size, shape, and spatial distribution (Weiss and Walsh, 2009). The treeline ecotone, commonly referred to as the treeline, timberline, or forestline, is the upper geographical limit of forests, representing vegetation zones between closed continuous forest and the treeless alpine zone (Körner and Paulsen, 2004). Treeline elevations range from near sea level in northern Canada and Alaska to 5000 m in the Andes (Troll, 1973). The recent rise in average global temperatures has apparently increased recruitment near treelines and led to their positions advancing upward, suggesting the need for careful monitoring to understand ecotone shifts in response to climate change. The occurrence of treeline altitudinal expansion appears to vary geographically, and evidence of this phenomenon is inconsistent across studies (Penuelas et al., 2007). Treeline altitudinal shifts are well documented in mountain ranges such as the Polar Urals of Russia (Devi et al., 2008) and the central Swiss Alps (Vittoz et al., 2008), but not observed in other studies on north Westland, South Island, New Zealand (Cullen et al., 2001), Glacier National Park, USA (Klasner and Fagre, 2002), and the central Tianshan Mountains, China (Wang et al., 2006). Moreover, while increased recruitment (of *Pinus* in the Pyrenees; Camarero and Gutierrez, 2004) and densification in the treeline ecotone (Chhetri and Cairns, 2015; Wang et al., 2016) have been observed in multiple studies, other research revealed tree density decreases and stable or shrinking treelines (Grace et al., 2002; Kullman, 2007; Zhang et al., 2010). These contradictory findings may be at least partially due to the lack of georeferenced treelines, a problem that can be addressed using remote sensing (RS) coupled with geographic information science (GIS).

Remote sensing technology obtains geographical data through satellite images or aerial photography that can be examined with GIS analytical methods. Monitoring of global ecological changes and biodiversity is among the most important contributions of RS (Pettorelli et al., 2014). More specifically, RS and GIS have been applied to the study of treeline ecology, increasingly supplementing the field-based ecological and dendroecological methods that dominate the discipline. Researchers can use RS images to detect treelines and then map them with GIS techniques (Danzeglocke, 2005). This supplementation is especially useful in low-accessibility, inhospitable regions like the Himalayas, where the expense and difficulty of field surveys can make collecting detailed information prohibitive (Mishra and Mainali, 2017). Furthermore, the wide availability of satellite images allows efficient data collection on a broad (landscape) to fine (individual patch) geographic scale. For example, RS sensors such as MODIS (moderate-resolution imaging spectroradiometer) and Landsats are capable of landscape-level images, while higher-resolution satellite sensors like GeoEye, IKONOS, and SPOT (Satellite Pour l’Observation de la Terre) can achieve patch- or even tree-level images.

Such advances in imaging provide a unique perspective for detection, measurement, and monitoring of biophysical factors associated with treelines and their spatial variability over time. These data lend themselves to conservation applications such as habitat mapping of treeline species or track habitat losses and gains to assess potential threats from climate change (Baker et al., 1995; Chhetri et al., 2017; Nagendra, 2001), all difficult to achieve with traditional field surveys but far more cost-effective using remotely sensed data with GIS (White et al., 1995; Xie et al., 2008).

In this study, I performed a meta-analysis on RS and GIS use in published research on the alpine treeline ecotone. My first objective was to investigate where and how RS and GIS have been applied in treeline-related work. My second objective was to identify common problems associated with RS and GIS in treeline research, as well as techniques used to address them. Finally, my third objective was to examine any existing gaps in RS and GIS application to treeline ecology.

MATERIAL AND METHODS

I performed independent literature searches in the following databases: Web of Knowledge (Thomson Reuters; https://apps.webofknowledge.com/ accessed on 01/27/2017), Scopus (Elsevier), BASE (Bielefeld Academic Search Engine; http://www.base-search.net/; accessed on 01/28/2017), CAB Direct, and Google Scholar. The following search terms were used: treeline, tree line, forestline, forest line, timberline, timber line, treeline ecotone, alpine treeline, remote sensing and treeline, GIS and treeline, RS and treeline, treeline position, treeline mapping, treeline advance, as well as treeline shift (Fissore et al., 2015; Muller et al., 2016). I assumed that prior to 1980, RS and GIS were uncommon in ecology; thus, I only considered articles published from January 1980 to January 2017. I specifically focused on publications related to the alpine treeline ecotone and examined their primary data sources, ancillary data sources (Digital Elevation Model [DEM], aerial or field photographs), principal techniques, data organization (classification approach, manual digitization, algorithm), procedures to address image resolution, pre-processing, and post processing issues, as well as accuracy assessment methods. I also noted the main research questions addressed, including mapping current treeline position, analyzing treeline shift, and factors controlling treelines.

RESULTS

General description

I examined 556 treeline-related publications from 1980 to 2017, extracting 103 studies that used RS and GIS solely or combined with other techniques to understand treeline dynamics. Four were book chapters, six were conference proceedings, and the remaining were peer-reviewed articles. Most publications originated from North America, but regions worldwide were represented (Figure 2-1a). I observed an increasing frequency of

RS and GIS use beginning from 2000 (Figure 2-1c), either independently or in combination. The majority of studies did the latter (Table 2-1).

Remote sensing at various spatial resolutions have been used in treeline studies, from low-resolution MODIS (250 m; Danzeglocke, 2005), moderate-resolution Landsat (30 m) to high-resolution GeoEye images (0.5 m, Chhetri et al., 2017) and aerial orthophotos (1 m, Wallentin et al., 2008; Walsh et al., 2003) (Table 2-2). Most papers published in the 1990s used RS images generated from Landsat MSS (Multispectral Scanner) and TM (Thematic Mapper), as well as SPOT PAN (Panchromatic) and MX (Multispectral) sensors. Recently, satellite images from ALOS (Advance Land Observing Satellite) (Guo et al., 2014), GeoEye (Chhetri et al., 2017), IKONOS, and WorldView-1 (Zong et al., 2014) have increased in popularity for mapping current and potential treelines (Table 2-3). Additionally, researchers are also taking advantage of freely available satellite images from ESRI basemaps, and Google Earth (Alatalo and Ferrarini, 2017; Jacob et al., 2017; Paulsen and Körner, 2014). In one such study, Klinge et al. (2015) used high-resolution ESRI-basemap satellite images to detect upper forest boundary in mountainous regions of semiarid central Asia. In developed nations, there is widespread use of modern RS techniques such as RADER (RAdio Detection And Ranging) and LiDAR (Light Detection and Ranging) (Weiss and Walsh, 2009), whereas the high costs associated with these techniques limit their use in developing nations. Finally, aerial photographs were mostly used for historical-change detection analysis (Luo and Dai, 2013; Mathisen et al., 2013).

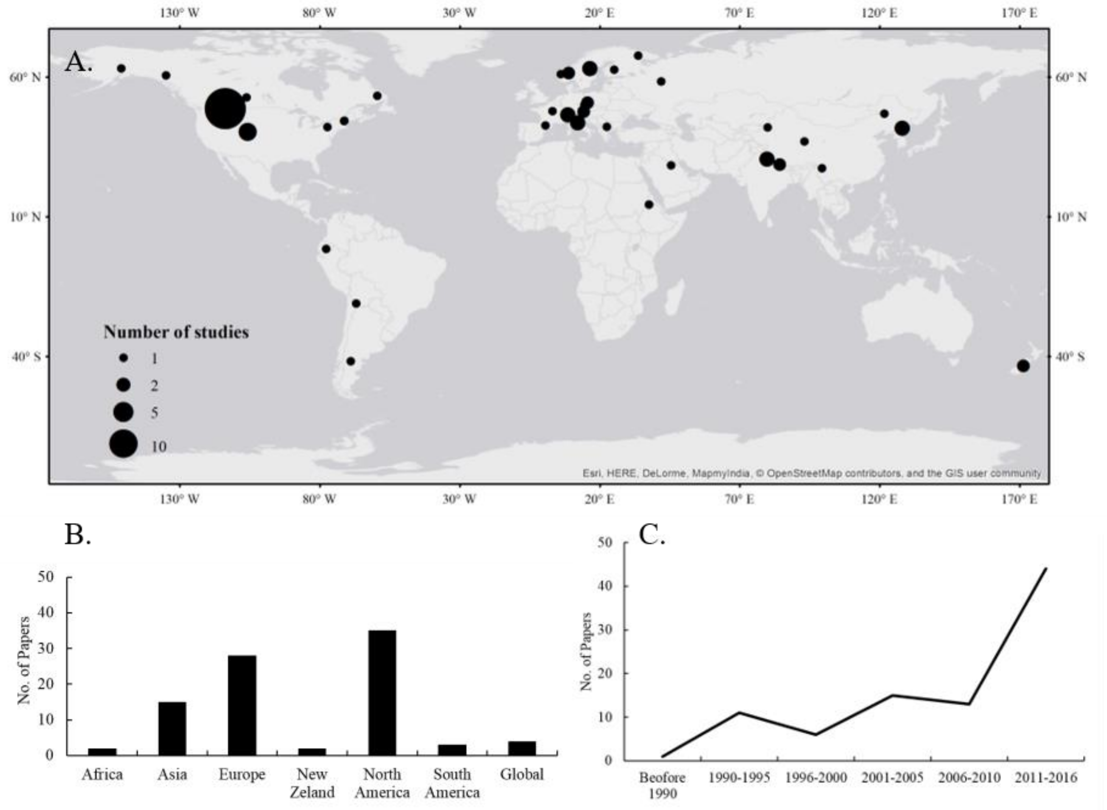

Figure 2-1: Summary of remote sensing (RS) and geographic information science (GIS)-related treeline studies. Breakdowns based on: A. study locations, B. study continents, and C. publication year

Table 2-1 Type of data use in treeline studies

Technique used	**No of papers**	**Top two published journals**
RS only	40	Geomorphology; Journal of Biogeography
GIS only	18	Arctic, Antarctic, and Alpine Research; Physical Geography
Aerial photos	16	Physical Geography; Arctic, Antarctic, and Alpine Research
Aerial photos, RS, and GIS	19	Journal of Vegetation Science; Physical Geography

Earlier studies using aerial photographs (Kimball and Weihrauch, 2000; Walsh et al., 1994; Walsh et al., 2003), Landsat TM (Allen and Walsh 1996; Brown, 1994a; Bryant et al., 1991; Walsh et al., 1992; Walsh et al., 2003; Virtanen et al., 2004), and Landsat ETM (Danzeglocke, 2005) images focused on treeline detection and identification. These included analysis of treeline elevation or spatial patterns (Allen and Walsh, 1996; Baker and Weisberg, 1995; Bryant et al., 1991; Danzeglocke, 2005; Kimball and Weihrauch, 2000; Walsh et al., 1992; Walsh et al., 2003; Walsh and Kelly, 1990); slope exposure effects (Paulsen and Körner, 2001), relations with topographic variables (Baker and Weisberg, 1995; Brown, 1994a), the influence of disturbances such as avalanches (Walsh et al., 1994), and predictive modeling (Baker and Weisberg, 1997; Walsh et al., 2003; Virtanen et al., 2004).

Table 2-2 An overview of satellite sensors used in treeline studies

Sensors	**Spatial resolution**	**Temporal range**	**No. of Publications**
ALOS	2.5 – 10 m	2006	1
AVHRR	1.1 km	1979	2
GeoEye	0.46 – 1.84 m	2008	2
IKONOS 1-2	1 – 4 m	1999	3
IRS	5.8 – 23. 5 m	1988	2
Landsat MSS	79 m	1972	5
Landsat TM	30 m	1982	22
Landsat ETM	15 – 30 m	1993	5
Landsat ETM+	15 – 30 m	1999	1
Landsat 8	15 – 30 m	2012	3
QuickBird	2 – 8 m	2001	3
MODIS	250 – 1000 m	1999	2
SPOT 1-5	2.5 – 20 m	1986	7
WorldView 1-2	0.46 – 1.80 m	2007	2

Table 2-3 Breakdown of different data sources used

Data Type	**Source of Data**	**No. of Papers**
Satellite imagery	GeoEye, IKONOS	11
Remote sensing imagery	Landsat, SPOT, MODIS	29
Aerial photograph	Orthophoto, orthoimages	16
Field photographs	Field photos	2
Digital elevation model	USGS, ASTER, SRTM	69
Topographic map	Survey department of studied Nations	3

Recent studies using GeoEye or IKONOS satellite imagery (Chhetri et al., 2017; Guo et al., 2014; Leonelli et al., 2016), hybrid cartographic models (Chhetri, 2017), and complex statistical modeling (Alatalo and Ferrarini, 2017) have focused more on potential treeline variation (Zhang et al., 2009). Topics include topographical factors controlling treeline (Bader and Ruijten, 2008; Guo et al., 2014; Leonelli et al., 2016; Resler, 2005), treeline patterns on multiple scales (Chhetri et al., 2017), quantifying advance rate (Leonelli et al., 2016; Zhang et al., 2009), models of treeline dynamics (e.g., with individual-based modelling; Wallentin et al., 2008), and future expansion in climate-change scenarios (Alatalo and Ferrarini, 2017; Chhetri, 2017). For instance, several works combined field data, DEM, and statistical techniques (logistic regression) to investigate mass elevation effects on the altitudinal distribution of global treelines

(Yao and Zhang, 2014; Zhao et al., 2014; Zhao et al., 2015). Recent studies also paid more attention to variation in species comprising the treeline, such as examining vegetation cover change in the treeline ecotone (Gartzia et al., 2014; Potter, 2016), and combining RS with species distribution modeling to predict future distribution trends of treeline-forming species (Braunisch et al., 2016; Chhetri et al., 2017)

Many studies have used GIS to generate DEM and extract geomorphic parameters (slope angle, aspect, relief, and curvature) to explain treeline structure. I found that ASTER DEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer – Digital Elevation Model) was among the most widely used (Yao and Zhang, 2014). Notable research includes Bryant et al. (1991), who tested the hypothesis that elevation and topographic exposure control treelines via DEM- and Landsat TM-based models of New Hampshire's White Mountain. Additionally, Kimball and Weihrauch (2000) used DEM data to correlate elevation, aspect, slope percent, and slope shape (concave to convex) with alpine plant distribution pattern throughout New England, USA. Digital elevation models produced from GeoEye panchromatic images were used to analyze elevational changes to the treeline in the Khibiny Mountains of Russia (Mathisen et al., 2013). Treeline studies using DEM also examined how solar radiation potential, soil moisture potential, and snow potential affected the treeline (Allen and Walsh, 1996; Brown, 1994a; Walsh et al., 1994; Walsh et al., 1998).

Statistical techniques used in treeline studies

The most common statistical techniques were unsupervised (Guo et al., 2014) and supervised maximum likelihood (Gartzia et al., 2014; Klinge et al., 2015) land cover classification, which have been used to map treelines. Others commonly used techniques are normalized difference vegetation indices (NDVI), image ratioing, principal component analysis (PCA) (Walsh and Kelly, 1990; Zhang et al., 2009), and visual interpretation (Groen et al., 2012; Chhetri et al., 2017; Stueve et al., 2011). Logistic regressions are frequently employed to clarify how topography controls current and future treelines (Bader and Ruijten, 2008; Brown, 1994a; Virtanen et al., 2004; Zong et al., 2014), including mass elevation effects on treeline position (Zhao et al., 2014, 2015). Correlation analyses and quadratic polynomial curve fitting were also commonly applied to study topography effects on treelines (Guo et al., 2014).

Specific applications of RS and GIS in treeline studies

Remote sensing and GIS have been used for various purposes in treeline studies (Table 2-4). I detail the most widespread applications below.

Treeline mapping

Treeline mapping is intended to accurately quantify treeline structure, improving our understanding of regional and landscape-scale variation over time, while also allowing us to differentiate between climatic, anthropogenic, and topographic treelines (Chhetri et al., 2017; Leonelli et al., 2009). Such data are useful for monitoring treeline response to climate change (Allen and Walsh, 1996; Chhetri et al., 2017). Mapping has been performed with Google Earth and GeoEye images (Chhetri et al., 2017; Leonelli et al., 2009), Landsat TM and ALOS images (Guo et al., 2014; Walsh and Kelly, 1990), and aerial photographs (Bakker and Weisberg, 1995; Resler et al., 2005).

Climate change and treelines

Remote sensing and GIS can detect treeline position and density changes in climate-change conditions, allowing us to model treeline sensitivity and potential advancement under warming temperatures. Studies in this category are classified as investigating either observed or predicted treeline variation.

Research focusing on observed variation, for example, included studies that employ multitemporal Landsat MMS and TM images to obtain NDVI values for quantifying treeline change. Alterations to treeline position were observed in some instances (Zhang et al., 2009) but not in others (Klasner and Fagre, 2002). Research focusing on predicted variation combined climate models with GIS, DEM, and current treeline position to understand potential changes under different climate change scenarios (Moen et al., 2004). Similarly, another study assessed how expansion could contribute to climate change via decreasing albedo above the forestline (Wit et al., 2014). Relatively few studies have attempted to test factors that can prevent treeline advancement. For example, Alatalo and Ferrarini (2017) investigated how climate and topography could act as brakes on global-warming-induced upslope forest expansion.

Factors controlling treelines

Researchers have also employed RS and GIS to understand the effects of other factors that structure the treeline structure, such as topography or geomorphology. Multiple studies exist that investigated how the alpine treeline ecotone may be influenced by topographic variables like snowfall patterns and avalanches (Guo et al., 2014; Walsh et al., 1994; Walsh et al., 2003), aspect and slope (Chhetri et al., 2017; Guo et al., 2014; Wang et al., 2013), topoclimatic variables (Case and Buckley, 2015), as well as solar radiation and soil moisture (Guo et al., 2014). A few studies (e.g., Bader and Ruijten, 2008) have examined the combined effects of all these variables on treeline patterns using statistical methods such as logistic regression models. The importance of geomorphological factors have prompted various recommendations (Chhetri et al., 2017; Leonelli et al., 2011; Macias-Fauria and Johnson, 2013) of incorporating such variables in all studies on treeline dynamics and expansion areas under climate change.

Table 2-4 Breakdown of studies based on their reasons for using RS and GIS

Purpose	**No. of Papers**
Mapping treeline	19
Analyzing treeline spatial pattern	14
Quantifying advance rate or change detection	17
Identifying control of treeline	20
Treeline structure	11
Habitat suitability modeling	12

DISCUSSION

General discussion

One of the earliest reviews (Roughgarden et al., 1991) synthesizing RS applications in ecology emphasized the availability of data on large and synoptic scales. Based on information in this publication, I determined that ecologists had begun to use RS technology for addressing ecological problems as early as 1984. The use of GIS in ecology began a little later, with the earliest example being Steyaert and Goodchild (1994). Soon after, RS and GIS were integrated to detect ecological boundaries like the treeline ecotone (Fagan et al., 2003; Tueller, 1999). As described, GIS was mostly used in early treeline studies for mapping and to develop models that linked topography with treeline vegetation structure (Brown, 1994a, b). Overall, I found that most studies in the meta-analysis primarily focused on understanding the quantitative effects of climate change on the treeline ecotone.

The majority of the included studies originated in the USA, likely due to the country's free and widely available RS and GIS data. The US Geological Survey, US Agriculture Department, and the National Mapping Center in Denver provide huge repositories of RS images (including satellite), DEMs, and aerial photographs. Furthermore, these resources are easily accessible via search tools such as http://earthexplorer.usgs.gov/. While a relative lack of resources can explain the lower number of studies from elsewhere, the dearth of work from South America is probably because few treeline sites are present. Overall, however, RS and GIS use in treeline studies are on the rise due to greater availability of RS imagery, increased presence of high-resolution satellite sensors in space, as well as the development of techniques to address pre- and post-processing issues. Importantly, RS and GIS have numerous advantages that make them highly desirable in treeline studies.

Advantages of RS and GIS in treeline studies

Vegetation mapping using RS data with GIS is very cost-effective (White et al., 1995), and its continued application will play an important role in detecting, quantifying, and analyzing environmental response to global climate change (Baker et al., 1995). Besides being beneficial for reaching low-accessibility areas (Klinge et al., 2015), RS and GIS approaches can allow researchers to find undisturbed treelines that are appropriate for the field sampling (Holtmeier and Broll, 2005). Remote sensing and GIS also improve treeline classification (e.g., (Chhetri et al., 2017), which is useful for determining what treelines (topographic, anthropogenic, or climate) are of interest in a particular study and will also enhance treeline monitoring efforts. Moreover, RS and GIS are increasingly critical for identifying regions of potential change under global warming (Guo et al., 2014), including where treelines might advance (Baker and Weisberg, 1997; Chhetri, 2017).

Another key advantage to RS and GIS approaches is the increase in flexibility, from landscape or regional studies to fine-tuned local studies. This flexibility is particularly important because various factors (e.g., geological history, lithology and structure, geomorphic process and landforms, and geologic and geomorphic factors) influence treelines across broad spatial scales (Butler et al., 2003). Combining RS and GIS approaches with field data can address these multiple factors and vastly improve our understanding treeline dynamics (Zhang et al., 2009). In areas where field-based approaches are not possible at all, RS analysis based on automated-image processing offers a fast and reliable alternative (Klinge et al., 2015) for change-detection, forest-densification, and shrub encroachment studies (Gartzia et al., 2014). Furthermore, high-resolution satellite imagery is invaluable to studies of micro-scale patterns, species composition, and structure at treelines. For example, the latest LiDAR technology can clarify canopy structure along the treeline ecotone, providing data on how such structural characteristics influence treeline response to climate change. In sum, these benefits are the major reasons behind the substantial increase in treeline studies employing RS and GIS when they are available. However, these technologies do have several drawbacks that should be considered when electing to use them.

Problems and potential solutions associated with RS and GIS in treeline studies

Multiple factors can influence the reliability of treelines mapped or analyzed using RS and GIS, including data type, image quality, georeferencing errors, DEM-related errors, accuracy of ground-control points, topographic or atmospheric effects, and digitization/interpretation errors (Groen et al., 2012). In the early years of applying RS and GIS to treeline science, researchers were primarily confronted with problems related to spectral, spatial, and temporal resolutions of RS imagery and DEM (Walsh and Kelly, 1990). Prior to index calculation or land-cover classifications, preprocessing of RS data and predetermination of geographic references were necessary to reduce biases that could lead to mapping errors (Walsh et al., 1998). Preprocessing steps included radiometric, atmospheric, geometric, and topographic corrections. In both early and recent studies (Guo et al., 2014; Walsh et al., 1998; Walsh and Kelly, 1990; Zhang et al., 2009), I noted relatively little mention of the exact techniques used to address potential problems. However, I was able to gather that early techniques used for atmospheric correction were TM ratio (Walsh and Kelly, 1990) and histogram normalization (Allen and Walsh, 1996; Walsh et al., 1994), while a more recent correction was ATCOR 3

(Atmospheric Correction for Flat Terrain) (Braunisch et al., 2016; Danzeglocke, 2005; Gartzia et al., 2014). For image enhancement, techniques such as PCA (Walsh et al., 2003), channel ratio (Walsh et al., 1994), and filters (e.g., low-pass and edge-detection; Danzeglocke, 2005) were used.

Another image processing challenge is topographical effects on spectral responses; this phenomenon occurs as a consequence of terrain and daily/seasonal changes to solar geometry, which causes illumination differences (Bishop et al., 2003; Walsh et al., 2003). Thus, rough and complex terrain in mountainous regions can complicate the detection and assessment of alpine treelines. Similarly, areas with high topographic relief, such as the Barun Valley of Eastern Nepal, present issues of highly variable illumination angles and reflection geometry (Zomer et al., 2002). In response, topographic normalization techniques were used to reduce such effects on the spectral reflectance of vegetation, thereby improving land cover classification and treeline identification. A common normalization method is an empirical regression model based on forest cover reflectance and solar illumination (Allen and Walsh, 1996).

Errors can also occur during orthorectification of aerial photographs due to imprecise location and digitization of control points (Baker and Weisberg, 1995). For example, areas with relatively few stable ground control points (GCPs) and few obvious features identifiable on air photos pose major challenges for georectification (Walsh et al., 2003). In an effort to reduce the usage of problematic aerial photographs, researchers have provided threshold values: the maximum acceptable root mean-square error during georectification should be less than half of their initial spatial resolution (Simms and Ward, 2013).

Multi-sensor errors arise when comparing data (e.g., NDVI ratio) from one sensor to data from another (Zhang et al., 2009). For example, resolution matching between historical and modern photographs (e.g., to quantify treeline shift) is a frequent source of error, as most historical images are lower in resolution than current images, and their validity cannot be confirmed as field data are frequently unavailable (Simms and Ward, 2013). Thus, in analyzing historical photographs, spatial interpolation techniques such as nearest neighborhood distance and bilinear interpolation (Bader and Ruijten, 2008) are used to improve resolution. Similar methods are also applied to reduce error when matching the spatial resolution of DEM with RS images, or when resampling one imager to match the resolution of another. These issues with resolution matching make clear that high-resolution images have both advantages and disadvantages.

Most high-resolution satellite images from GeoEye, Worldview, and Quickbird have a short history of data availability, meaning they are less suitable for any long-term change detection studies. Furthermore, image availability is frequently diminished by the severe climate in alpine areas (Zhang et al., 2009). For example, the Himalaya region is under cloud cover from June –September due to the monsoon season. Although this problem can be mitigated with cloud-penetrating RS techniques such as microwave synthetic aperture radar (SAR) imaging, their high cost limits widespread use. High resolution imageries cover small areas and frequently take up considerable harddrive space. In contrast, low-resolution image are free, cover large areas, and are easy to store.

Despite their relative prevalence, DEMs have several issues. First, high-resolution DEMs are inaccessible for most developing countries. Currently, occasionally error-prone ASTER DEM, at a spatial resolution of 30 m, is the highest resolution freely available. Existing errors in ASTER DEM are compounded by the fact that it is typically used for generating data such as aspect, slope, curvature, surface roughness, and solar radiation index. Such data are then used to analyze variables including treeline spatial patterns and slope exposure. Thus, the accuracy of the initially generated data will affect subsequent analyses, potentially multiplying any errors. Several techniques have been proposed to remove low-quality and terraces in DEMs (Bader and Ruijten, 2008).

The application of RS and GIS in treeline advancement or change-detection studies can lead to over- or underestimation because researchers frequently cannot detect seedling/sapling densification or recruitment. Combining RS and dendroecological methods considerably minimizes this risk (Mathisen et al., 2013; Treml et al., 2016). Indeed, balancing between these two approaches can produce high-quality data that helps us understand climate-change effects on the treeline ecotone.

Future directions for RS and GIS applications in treeline studies

Remote sensing and GIS are widely popular techniques used in treeline studies that can complement field-based research. Further, a number of newly developed techniques can address many of the associated errors and accuracy-related issues of RS and GIS. For example, atmospheric effects in RS imaging can be removed via corrections such as ATCOR2 (Atmospheric Correction for Flat Terrain), the COST model (Cosine of the Sun Zenith Angle; (Chavez, 1996), FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes), and 6S (Second Simulation of Satellite Signal in the Solar) (Lopez-Serrano et al., 2016). Similarly, topographic corrections can be performed with methods such as the sun-canopy-sensor (SCS; (Gu and Gillespie, 1998) and SCS+C (Gao and Zhang, 2009). Orthorectification-related issues in aerial photograph digitization can be minimized through collecting precise ground control points using differential GPS. Finally, multi-sensor calibration issues can be addressed using methods such as the empirical line approach for Landsat 5 TM to Landsat 7 ETM+ (Moran et al., 2001).

Various models can incorporate RS and GIS to predict future treeline advancement, including the habitat suitability model and species distribution model. This combined approach will help us understand how treeline advancement may fragment the alpine ecosystem, and how it may influence the habitats of endangered species. Remote sensing and GIS can also be incorporated into process-based modeling to understand treeline dynamics more systematically (Wallentin et al., 2008). Moreover, historical aerial photographs can overcome issues of long-term availability associated with high-resolution satellite imagery (Luo and Dai, 2013). I also look forward to the high potential of RADAR and LiDAR as they become more available to developing countries. Future treeline studies can look forward to aerial photographs taken by unmanned aerial vehicles (UAVs), RS images with high spatial- and radiometric-resolution, as well as increased accessibility of high-resolution DEM. With the help of these technologies, standardized, repeatable, and long-term results should become possible (Groen et al., 2012), contributing to the creation of managers strategies that conserve the alpine ecosystem against advancing treelines.

CONCLUSIONS

Geographic Information Science analysis combined with high-resolution RS imagery can be used for mapping the treeline ecotone, quantifying treeline advancement rate, and monitoring treeline change. The use of RS and GIS in treeline studies is increasing rapidly as these resources become more widespread and their advantages become well-known. Notably, RS and GIS techniques increase the scale at which treeline studies can be performed, ranging from low-resolution, regional-level to high-resolution, patch-level research. In closing, there is no doubt that RS and GIS will greatly advance ecological research, especially given the rapidly improvements to such technologies and the increasing availability of high-resolution satellite images. The future will bring new data products with higher spectral and spatial resolution. There is therefore a need to have a toolkit ready to process data in a way that ensure similar sites are compared.

CHAPTER III

CURRENT POSITION, TYPE, AND SPECIES COMPOSITION OF TREELINE AT REGIONAL AND LANDSCAPE SCALE *

INTRODUCTION

The treeline ecotone represents high elevation vegetation zones between closed continuous forest below and the treeless alpine zone above, and constitutes forestline (line connecting uppermost patches of forest) and treeline (the line connecting uppermost trees) (Körner, 2012). Most of the early treeline research was limited to investigating the role of climate on treeline dynamics and potential response of treeline to climate change (McDonald et al., 1998; Wang et al., 2006). Recently, the role of human activities such as agropastoralism (Piermattei et al., 2012), and landforms and topography (Elliott, 2012; Holtmeier, 2012) in treeline structuring processes have been analyzed. Researchers have also shifted their interest toward using Remote Sensing (hereafter RS) and Geographic Information Science (hereafter GIS) in studying the geomorphic processes and patterns at treeline (Butler et al., 2007; Walsh et al., 2003), and treeline position change (Bharti et al., 2012; Singh et al., 2012). Recently, Szerencsits (2012) produced a paper on GIS based approximation of treeline in the Swiss

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* Chhetri P.K. Shrestha K.B. and Cairns D.M. 2017. Topography and human disturbances are major controlling factor in treeline pattern at Barun and Manang area in the Nepal Himalaya. *Journal of Mountain Science* 14 (1):119-127

Alps, and mentioned that availability of high resolution land cover information provides new opportunities for GIS based approach in treeline study.

Remote sensing is a widely used technique for detecting forestline and treeline positions (Zong et al., 2014). Remotely sensed vegetation mapping using digital geographical data is cost-effective (White et al., 1995), and will play an important role in detecting, quantifying, and analyzing the spatial responses of landscapes to global climate change (Baker et al., 1995). The use of imagery is particularly useful in rugged and inaccessible terrain of the Himalaya. Treeline ecotones are important landscapes, and need monitoring in the context of global climate change. Only a few data are available on the treeline characteristics at regional and landscape scales from the Nepal Himalaya. Studies carried out so far (Chhetri and Cairns, 2015; Gaire et al., 2014; Schickhoff et al., 2015; Shrestha et al., 2014; Suwal et al., 2016; Tiwari et al., 2016) have focused on treeline pattern at local (plot) scale only using a dendroecological approach. In the Nepalese Himalaya, treeline ecotones are characterized as climatic (natural), orographic, or anthropogenic. Therefore, landscape scale studies on climatic, topographic and anthropogenic treeline are needed. RS and GIS based treeline mapping at the regional and landscape scales will elucidate species composition, current treeline positions, slope exposure effect and treeline type. Therefore, in this study I am addressing two main research questions: 1) what is species composition and spatial pattern of treelines? (2) how and why do treelines differ across different locations? To address these research questions I mapped and analyzed treeline at the regional scale covering the entire Nepal, and that at the landscape scale focusing on Barun and Manang Valley.

MATERIALS AND METHODS

Study area

Nepal is a mountainous country located between 26°22′, 30°27′ N and 80°04′, 88°12′ E, and occupies the central part of the Himalaya. The country has an east-west distance approximately 1000 km, the north-south extent is approximately 200 km, and the area 147181 km^2. The elevation ranges from 60 m in the south to over 8000 m in the north (Figure 3-1), which could contribute in a complex topography and varied climate. Nepal is primarily influenced by the South Asian monsoon in summer and westerly winds in the winter. It receives more than 80% of its total precipitation during the summer monsoon, and varies along an east to west gradient. Due to this variation in climatic patterns and topography, Nepal has climates ranging from tropical to alpine, and contains the vegetation zones that are associated with these climates.

U-shaped Barun Valley (Figure 3-1) is located in the north of the Makalu Barun National Park (hereafter MBNP), Sankhuwasabha, Eastern Nepal. The valley shows evidence of Pleistocene glaciation at the elevational belt of sub-alpine forests (Carpenter and Zomer, 1996). The area receives pronounced rainfall during the monsoon period (June to September). *Abies spectabilis* (Himalayan silver fir) is the dominant tree species, and covers the treeline ecotone elevation, which ranges from 3800–4100 m (Chhetri and Cairns, 2015, 2016). Human disturbance, such as cattle grazing and timber harvesting, is minimal in the forests. Manang Valley is a part of the Annapurna Conservation Area (ACA), Manang, Central Nepal (Figure 3-1). The valley separates the Tibetan Plateau to the north and the main Himalayan axis of the Annapurna range to the south, and is part of the trans-Himalayan arid region of the country. The climate is characterized by warm dry summers with frequent strong winds, which produce xeric conditions. The treeline ecotone occurs between 3800–4100 m, and is dominated by *Pinus wallichiana* (Himalayan blue pine), *Betula utilis* (Himalayan birch), and *Abies spectabilis* (Himalayan silver fir).

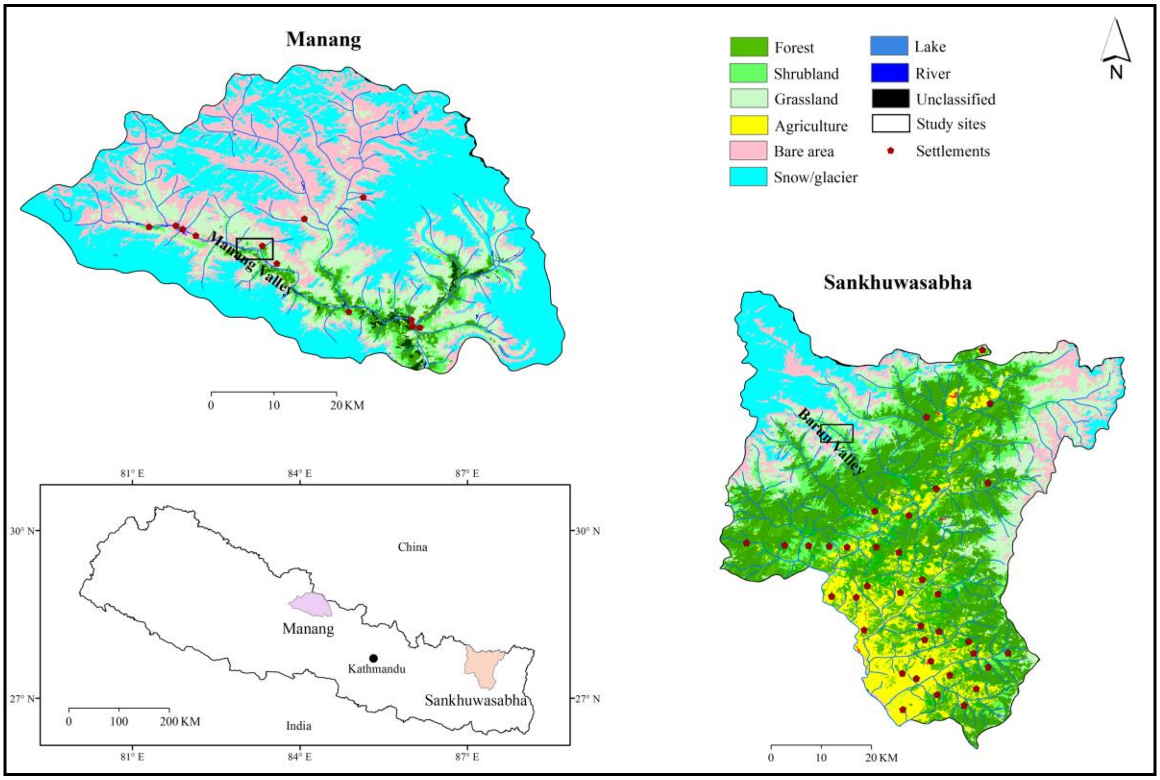


Figure 3-1: Study sites in Eastern (Sankhuwasabha - Barun Valley) and Central (Manang - Manang Valley) Nepal.

Treeline mapping and spatial pattern analysis

Regional scale

For mapping and analyzing the treeline at the regional scale, I used a land cover map prepared by the European Space Agency (ESA; 300-m spatial resolution) in 2010, a land cover map of Nepal prepared by the International Center for Integrated Mountain Development (ICIMOD; 30m spatial resolution; Uddin et al., 2015) in 2010, and a GIS database of Nepal prepared by ICIMOD. I mapped treelines by connecting the uppermost forest patches (Paulsen and Körner 2001). The Shuttle Radar Topography Mission Digital Elevation Model (SRTM-DEM; 90-m spatial resolution) was obtained from the United States Geological Survey (USGS; http://earthexplorer. usgs.gov/; accessed on 14 November 2014), and was used for assigning elevations to the mapped treelines and generating slope angle and slope aspect maps. All of the mapped treelines were resampled to a 300-m resolution for further analyses. Ancillary data, such as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery, Google Earth imagery and topographic maps (1:50000, obtained from the Department of Surveys, Government of Nepal), GIS layers, field photographs, and field observations were also used. To verify the treeline mapping, Global Positioning System (GPS) locations of forty-one treeline sites were obtained from the field survey and published literature. These points were overlaid with the treelines in order to determine the accuracy of the regional treeline mapping.

Landscape scale

Preprocessed high-resolution Digital Globe images (GeoEye) for Barun Valley (0.5-m spatial resolution, acquired on 10 Nov. 2006) and Manang Valley (2 m spatial resolution, acquired on 11 Nov. 2008) were obtained from the Digital Globe Foundation. An ASTER DEM (30-m resolution) was obtained from the USGS (http://earthexplorer.usgs.gov/; accessed on 17 April 2014). Topographic parameters such as slope and aspect were generated using ESRI's ArcGIS 10.1 software. Treelines and forestlines were manually mapped using an interactive image interpretation procedure following tonal, textural, contextual, size, shape, shadow, association, and site patterns of the forest edge and uppermost patches of trees (Zong et al., 2014). Identification was also conducted using topographic maps, Normalized Difference Vegetation Index (NDVI)-based maps, supervised and isodata classification maps, and field-based knowledge. Ancillary data (previously obtained for the regional-scale treeline analysis) were incorporated into this phase of the analysis. All of the mapped forestlines and treelines were resampled to a 30-m resolution for further analyses. The DEM was used to assign the elevations of forestlines and treelines. Mean treeline elevation was calculated for each slope direction for both the study sites. An analysis of variance (ANOVA) was conducted to identify significant differences between sites and slopes. Mapping reliability was verified using field-based GPS locations. Forty and fifty-five random verification points were selected in Barun and Manang, respectively.

A climatic treeline is characterized by the absence of any rock outcrops or steep slopes immediately above the treeline, and a rock outcrop or steep slope above the treeline indicates a topographic treeline. Rock outcrops and steep slopes were identified by overlaying the contour lines. Treelines were classified as anthropogenic if human settlements were identified adjacent (near) to the treeline ecotone area. A slope map generated from the DEM was overlaid with the treeline map to calculate treeline slopes. The mean slope was calculated for each aspect using the DEM. I used Relative Radiation Index (RRI) to determine whether south-facing slopes received more solar radiation than other slopes (Oke, 1987). RRI was also used to see the relation between mean RRI value of aspect and treeline elevation.

Possible biases in our analysis

I assumed that the upper limit of a closed forest represents the treeline in the regional-scale analysis, because detecting trees in land cover maps with a 300-m spatial resolution is difficult. Errors in land cover maps or DEMs might have caused errors in treeline mapping. The ASTER DEM error was 15 m and the SRTM DEM error 90 m; therefore, the DEM error was within the range of ecotone lengths. However, the DEM error is systematic and independent of slope exposure (Paulsen and Körner, 2001).

RESULTS

Regional scale

Approximately 1800 km of treelines are mapped, and 80% of the field-based treeline observations matched the treelines generated here (Figure 3-2). The nonaligned 20% field-based treelines are attributed to either errors in the GPS coordinates or in mapping. *Abies spectabilis*, *B. utilis*, and *P. wallichiana* are the main treeline-forming species (Figure 3-2). In some locations (mostly central Nepal), treeline forming species are associated with other species, such as *Rhododendron campanulatum* (bell rhododendron) and *Juniperus indica* (black juniper). *Abies spectabilis* dominated treelines in eastern Nepal and *B. utilis* is the dominant treeline species in western Nepal. In central Nepal, *P. wallichiana, A. spectabilis,* and *B. utilis* formed the treeline. *Betula utilis* is the dominant treeline species on north-facing slopes and *A. spectabilis* is the dominant treeline species on south-facing slopes. Treeline elevation ranges between 3300–4400 m (Figure 3-2). Treelines in Eastern and Western Nepal are at higher and lower elevations, respectively, than 4000 m. *Juniperus indica* formed the highest treeline in Nepal, with a mean treeline elevation of 4421 m (Table 3-1). No slope-exposure effect is observed at the regional scale treeline pattern (Figure 3-3). Average treeline elevation of south-, north-and other aspects are similar.

Table 3-1 Mean treeline elevation of treeline species and dominating slope aspect based on regional-scale treeline analysis

Species	**Mean treeline elevation (m)**	**Mean aspect**
Birch	3918	North
Birch-Fir	4037	North
Birch-Rhododendron	3908	North
Fir	4050	South
Fir-Birch-Rhododendron	4041	South
Fir-Hemlock-Oak	3612	South
Fir-Pine	4070	South
Juniper	4421	South-West
Pine	3813	West
Pine-Birch	4288	South

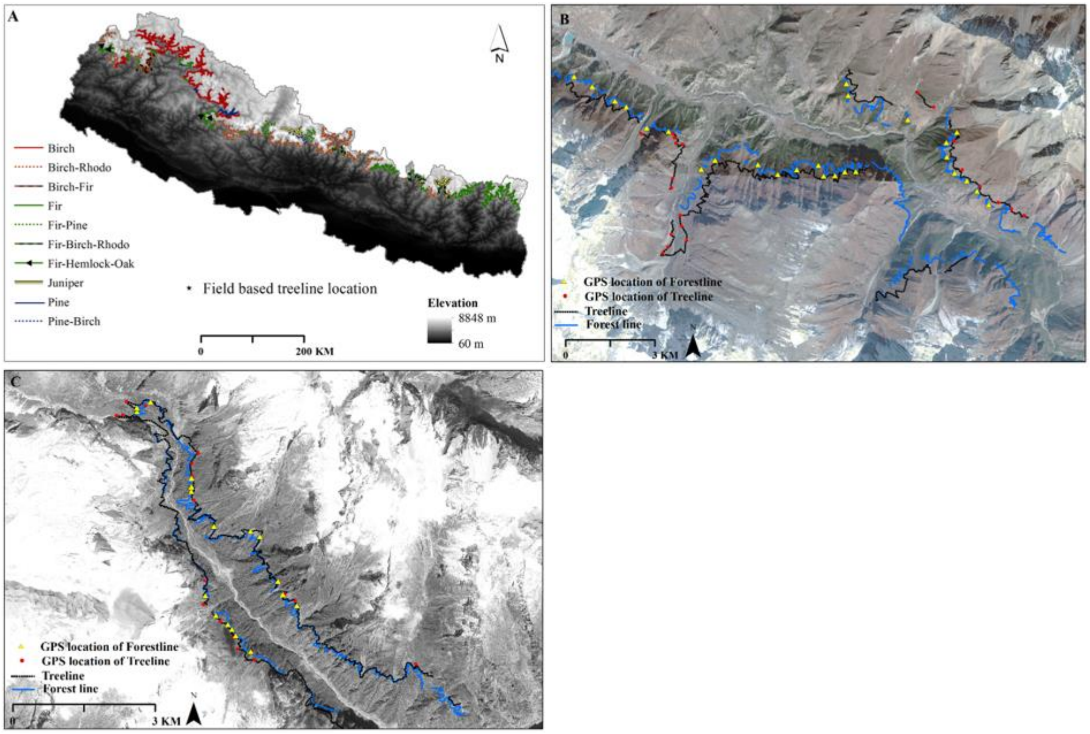


Figure 3-2: Nepalese regional (A) and landscape scale (B- Manang, C - Barun) treeline and forestline patterns. Yellow triangles are Global Positioning System (GPS) - collected forestline positions, and red circles are GPS collected treeline positions in the field. Sources: European Space Agency, International Center for Integrated Mountain Development, and Digital Globe.

Landscape scale

Forestlines and treelines at the two study sites are presented in Figure 3-2. The overall accuracy of the mapping is 83% (Table 3-2). Results from mapping revealed that the mean forestline elevations are higher in Barun Valley than in Manang Valley (Table 3-3). However, the mean treeline elevation is highest in Manang Valley. The highest treeline elevation (4218 m) is recorded in Barun Valley. Mean treeline ecotone length is calculated as 8 m and 154 m in Barun and Manang elevations significantly differed between the study sites (*n* = 2) (*F* = 112, *p*< 0.01). The mean treeline elevation is similar on different aspects in Barun Valley; however, in Manang Valley, the mean treeline elevation on south-facing slopes is lower than on north-facing slopes (Figure 3-3). When treeline elevation is considered regardless of study site, there is no significant variation with aspect (*n* = 8) (*F* = 0.03, *p* < 0.01). The highest treelines in Barun Valley are recorded on south-west- and south-east-facing slopes, whereas in Manang Valley they are found on west-facing slopes (Figure 3-4). South- facing slopes at all of the study sites have higher RRI values than north-facing slopes (Table 3-4). No relation is found between RRI and treeline elevation. Slope angles ranged from 19° to 37° and from 29° to 39° in the Barun and Manang valleys, respectively (Table 3-4). No significant relationship is found between slope angle and mean treeline elevation at both study sites. The majority of treelines in Barun Valley are of the topographic type whereas in Manang Valley, they are climatic (Figure 3-5). A small portion of Barun Valley treeline and major portion of south-facing slope of Manang Valley treeline is anthropogenic.

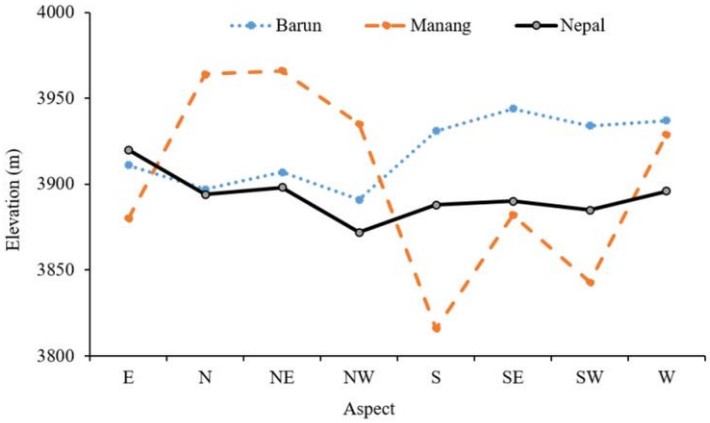


Figure 3-3: Mean treeline elevations at different slope exposures at two study sites and overall. Notes: Aspect: N = North, E = East, S = South, W = West.

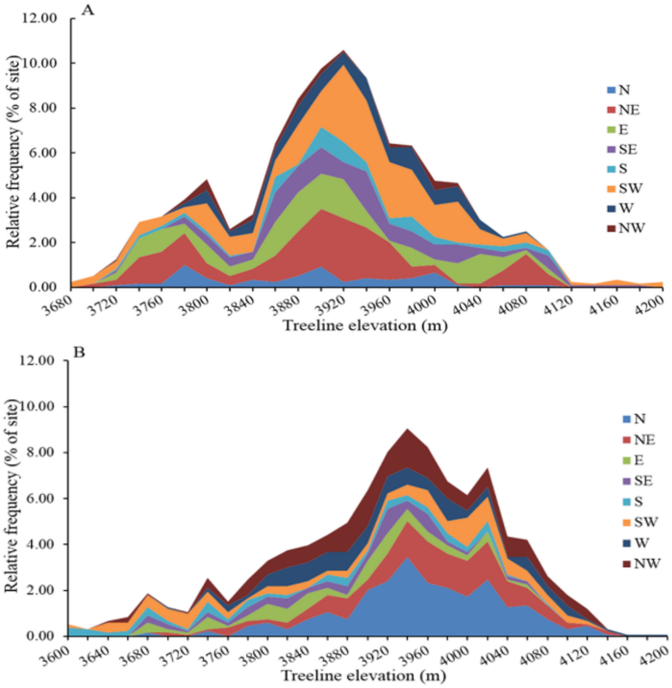


Figure 3-4: Frequency distribution of treeline elevations in respect to aspect at two study sites.

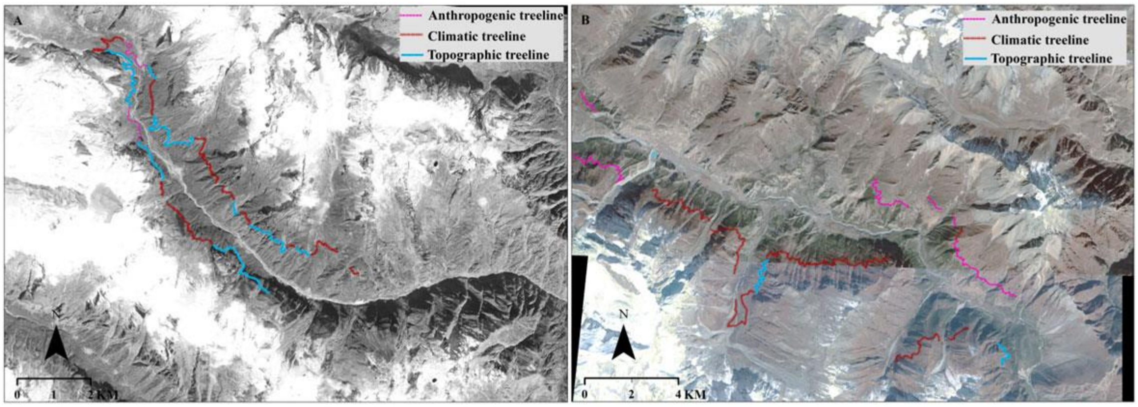


Figure 3-5: Treeline type (Anthropogenic, Climatic and Topographic) in A. Barun Valley and B. Manang Valley.

Table 3-2 Accuracy assessment of landscape-scale mapping results with field-based Global Positioning System (GPS) positions

Mapping classification	**Field-based GPS data (Reality)**				**Classification total**	**Accuracy**
	Barun		Manang			
	Forestline	**Treeline**	**Forestline**	**Treeline**		
Forestline	17	3	24	0	41	82%
Treeline	3	17	0	21	38	84%
Field-based total	20	20	30	25	Overall accuracy: 83%	

Table 3-3 Forestline and treeline elevations estimated from Digital Globe satellite imagery in two regions of Nepal

Elevation (m)	Barun	Manang
Forestline		
Maximum	4201	4066
Minimum	3574	3174
Mean	3915	3773
Standard deviation	86	175
Treeline		
Maximum	4218	4162
Minimum	3687	3560
Mean	3923	3927
Standard deviation	94	113

Table 3-4 Relationships between treeline elevation, slope angle, and Relative Radiation Index (RRI)

Aspect	Barun			Manang		
	Elevation (m)	Slope (degrees)	RRI	Elevation (m)	Slope (degrees)	RRI
East	3911	28	0.75	3880	29	0.72
North	3897	31	0.51	3964	32	0.48
North-East	3907	36	0.51	3966	29	0.59
North-West	3891	19	0.71	3935	33	0.53
South	3931	30	0.96	3816	39	0.95
South-East	3944	26	0.90	3882	29	0.89
South-West	3934	37	0.88	3843	37	0.89
West	3937	30	0.78	3929	33	0.69

DISCUSSION

Regional scale

This study has demonstrated the effectiveness of RS and GIS techniques for mapping forestlines and treelines. The results obtained from our regional mapping corroborate the information produced from other techniques (Chhetri and Cairns, 2015; Chhetri et al., 2016; Gaire et al., 2014; Schickhoff, 2005; Schickhoff et al., 2015; Shrestha et al., 2014; Suwal et al., 2016; Tiwari et al., 2016). *Abies spectabilis*, a dominant component of sub-alpine forest ecosystems of the Himalaya, forms the majority of the treeline in Nepal (Shi and Wu, 2013). *Juniperus indica* was the highest treeline-forming species in Nepal, as it is in Tibet, where the highest treeline in the Northern Hemisphere has been reported (Miehe et al., 2007).

This study demonstrated that treeline elevation decreases from east to west which follows the east-west decreasing pattern of monsoon rain (Stainton, 1972). Chaudhary (1998) reported a similar decreasing trend (4000 m at east, 3800 m at center and 3650 m at west). However, Brauning et al. (2004) and Schickhoff (2005) reported several treelines at elevations between 4100–4200 m in Western Nepal might be attributed to the continental climate of this region. However, long snow cover and the short growing season compensate for the favorable summer temperatures (Schickhoff, 2005). The east-west gradient of treeline elevation may also be a result of latitudinal variation; a decrease of one degree latitude roughly corresponds to a 100-m decrease in treeline elevation (Shi and Wu, 2013).

Landscape scale

Slope aspect is one of the main influencing factors on the vegetation structure and composition of treeline ecotones (Danby and Hik, 2007). This is because south-facing slopes are warmer, as they receive sunlight for longer diurnal periods than north-facing slopes (Dubey et al., 2003). The higher RRI values found on south-facing slopes (compared to north-facing slopes) at all of my study sites supported the above argument. Other studies have found no effect of slope exposure on treeline elevation (e.g., Paulsen and Körner, 2001; Wang et al., 2013) and my results are similar to those reported in these studies. I did not find any significant differences in treeline elevations between the Barun and Manang valleys. Interestingly, treelines on south-facing slopes in the Manang Valley were at lower elevations than those on north-facing slopes, suggesting human activities are responsible for lowering treeline below its potentiality. In this valley, south-facing slopes are more suitable for human settlement; therefore, they are affected by agropastoralism (timber and fuel wood harvesting, and clearing of the forest for increasing grazing area). The lower treeline elevation on south-facing slopes may also be related to a lack of sufficient water, as the valley is in a rain-shadow area and receives relatively low annual precipitation. North-facing slopes are less exposed to sunlight, and provide a suitable environment for shade-tolerant genera such as *Abies* and *Betula* (Paudel and Vetaas, 2014).

The large variations in treeline elevations at our study sites highlight the importance of regional as well as local factors in controlling treeline elevations. Based on treeline ecotone length, the treelines at both sites were of the diffused type. However, most of the treelines in the Barun Valley were topographic. Some climatic treelines were also observed. Geomorphic features such as steep slope, exposed rock surface, and active landform (landslide, rockslide) may control the majority of the treeline in Barun area. The north-facing slope of Manang Valley was dominated by climatic treelines, with only a few anthropogenic treelines. Majority of the treelines of the south-facing slope Manang Valley were anthropogenic treelines because of more favorable area for human settlements. In the Himalaya, south-facing slopes receive much more solar radiation than north. Therefore, majority of human settlements and pasturelands are located on the south-facing slope.

CONCLUSIONS

Abies spectabilis, *Betula utilis* and *Pinus wallichiana* are the main treeline forming species of the Nepal Himalaya. *Abies spectabilis* and *B. utilis* are dominant in the treeline ecotone of Barun and Manang Valley, respectively. Slope aspect is not important in determining treeline position at the regional scale. However, at the landscape scale, slope aspect affected treeline elevation, particularly at undisturbed locations. This indicated that factors controlling the treeline structure are strongly scale dependent. Treeline type delineation dominate Barun and Manang Valley respectively, suggesting that topographic and anthropogenic variables are the important factors in structuring the treeline ecotone. Information on treeline type obtained from this landscape scale study will help predict the responses of forestlines and treelines to temperature changes. Future studies investigating geomorphological and land use pattern near treeline, and treeline ecotone processes in order to understand treeline responses to environmental change in the Nepal Himalaya.

CHAPTER IV

LOW RECRUITMENT ABOVE TREELINE INDICATES TREELINE STABILITY UNDER CHANGING CLIMATE IN DHORPATAN HUNTING RESERVE, WESTERN NEPAL

INTRODUCTION

Alpine treeline ecotones are the upper limit of subalpine forest and one of the most distinct vegetation boundaries we have on the earth’s surface. Altitudinal treelines are a fundamental component of high-mountain landscapes that are strictly linked to past and present climate regimes. Therefore, they act as a reliable monitor of the impacts of climate change on vegetation dynamics, and documenting treeline dynamics provides an opportunity for predicting tree responses to future climate changes (Srur et al., 2014). It is believed that treelines will advance upward with temperature increases (Körner, 2012). Upward advances of treelines will fragment the alpine ecosystem and ultimately change the alpine landscape. However, to know with certainty whether a treeline will advance, we need to understand the different factors that control it. The causes of alpine treeline formation have been discussed extensively over the past 100 years (Holtmeier and Broll, 2007; Körner, 2012).

Temperature plays a primary role in controlling treeline position (Greenwood et al., 2015). Treelines are advancing in response to a warming climate throughout the globe (Greenwood et al., 2015). Most of the underlying hypotheses of this advance are linked to climatic drivers, and growing seasonal temperature is the most widely acceptable primary control. Therefore, treelines should shift upslope in response to rising global mean temperatures. Treelines may respond rapidly to climate warming by exhibiting changes in elevation and structure, and there is considerable interest in investigating variations in treeline position and identifying the mechanisms of treeline formation. Several studies have been carried out to account for this change in treeline ecotones worldwide. Treelines can respond to climate change in various ways, such as treeline position shift, infilling of the treeline ecotone, increase in recruitment, decrease in mortality rate, increase in radial growth, and increase in intermodal growth pattern. Many studies have indicated that treelines are advancing and that this advancement is directly related to recruitment pattern. Many advancing treelines have high recruitment above the treeline or have shown an increase in density of individuals within the ecotone (Truong et al., 2006). Studies carried out in areas like Canada, Norway, and the Indian Himalayas indicate treeline advance; where as some treelines are stable in the Rocky Mountains (United States), Europe, and New Zeeland. Moreover, this mixed trend is reflected in Harsch et al. (2009) study, in which they reviewed more than 200 studies from 166 sites. They found that the treeline had advanced in 52% of the sites, remained stable in 47% sites, and receded in 1% of the sites. They also noted that at most of the 166 sites, temperatures had increased. Many studies have indicated that infilling is occurring within the treeline ecotone rather than treeline advance (Ameztegui et al., 2016; Batllori et al., 2009; Camarero and Guiterrez, 2004). Therefore, no clear trend exists to support the hypothesis that treelines are advancing in response to climate change and treelines are advancing in one particular area and not in another.

Studies in Nepal have reported mixed findings: some indicated a stable treeline (Schwab et al., 2016; Shrestha et al., 2014), others reported that the treeline had shifted upward (Gaire et al., 2014; Suwal et al., 2016; Tiwari et al., 2016), and others found that infilling or densification had occurred (Chhetri and Cairns, 2015; Gaire et al., 2016). Therefore, there is spatial heterogeneity in the treelines of Nepal (Schwab et al., 2016), so more studies on these understudied areas and diverse tree species are needed to understand the treeline dynamics. Most of the treeline-related studies from Nepal are concentrated on gymnosperms species such as *Abies spectabilis* (Chhetri and Cairns, 2015; Gaire et al., 2014). Very few studies (Gaire et al., 2016) focus on angiosperms like *B. utilis*. Thus, it is hard to know how *B. utilis* treelines are responding to recent temperature changes. This is important because in the Nepal Himalayas, *B. utilis* forms the highest treeline (above *A. spectabilis*) (Shrestha et al., 2007), and *B. utilis* is the most dominant treeline-forming species in the Nepal Himalayas (Chhetri et al., 2017). In this study, I established two transects in Western Nepal to understand the treeline dynamics of *B. utilis* and addressed the following research questions: (a) is rising temperature triggering an increase in recruitment at the treeline ecotone? and (b) is the availability of suitable regeneration microsites an important factor limiting establishment above the forestline? I addressed these research questions by comparing age structure and recruitment above and below the forestline and by analyzing the spatial pattern of individual establishment.

MATERIALS AND METHODS

Study area

This study was carried out in the Rugakharka area at the Barse Block of the Dhorpatan Hunting Reserve (DHR), Western Nepal (Figure 4-1). DHR was established in 1983 and gazetted in 1987; it covers an area of 1325 km^2, and its elevation ranges from 2000–7246 m. The DHR covers 26.42% of the Baglung District, 14.13% of the Myagdi District, and 59.45% of the Rukum District of Nepal (Karki and Thapa, 2007). The climate of the DHR varies from sub-tropical in the lower elevation to alpine in the higher elevation zones. The average annual temperature of the reserve is 6.3°C, and the annual precipitation is > 1000 mm (Figure 4-2a). Long-term climatic research unit (CRU) climate data indicate an increasing temperature trend ($y = 0.0085x - 10.20$, $R^2 = 0.31$, $p < 0.01$, $n = 114$) and a decreasing precipitation trend ($y = -0.154x + 424.37$, $R^2 = 0.07$, $p < 0.05$, $n = 114$) for the region (Figure 4-2b). Seasonal trend analysis of temperature and precipitation data indicate a significant temperature rise in winter ($y = 0.0139x - 28.41$, $R^2 = 0.36$, $p < 0.01$, $n = 114$) and autumn ($y = 0.0116x - 18.10$, $R^2 = 0.23$, $p < 0.01$, n =

114), and a significant decrease in precipitation in summer ($y = -0.045x + 110.05$, $R^2 = 0.14$, $p < 0.05$, $n = 114$) seasons (Figure 4-2c,d,e,f).

Common flora of the reserve are *Abies spectabilis* (silver fir), *Betula utilis* (birch), *Pinus wallichiana* (blue pine), *Quercus semecarpifolia* (oak), *Rhododendron arboretum*, and *Rhododendron campanulatum* (rhododendrons). Common fauna are *Pseudois nayaur* (blue sheep), *Nemorhaedus goral* (goral), *Hemitragus jemlahicus* (Himalayan tahr), and *Moschus chrysogaster* (Himalayan musk deer) (Karki and Thapa, 2007). The ground is covered with moss and litter. *Betula utilis* is a dominant tree species in the treeline ecotone of DHR. Buki (Tussock) grass (*Carex sp*.), *R. anthropogen*, and *Cassiope fastigiata* are the dominant species above the treeline.

Study transects were established in the upstream area of Simudar Khola. In the upper Simudar Khola Valley, the subalpine forest extends from 3550–3900 m. In the valleys, the forest is dominated by *A. spectabilis*, and associated species are *B. utilis* and *R. companulatem*. Above 3700 m, *B. utilis* is the dominant species. Human disturbances were minimal in the treeline ecotone area. Only a few cut stumps were present; cattle dung and fire marks were absent. Cattle grazing (water buffalo) is concentrated near lower-elevation river valleys, and many grazing sites were observed during the field visit. However, in the open area above the treeline, domesticated sheep and wild sheep were present.

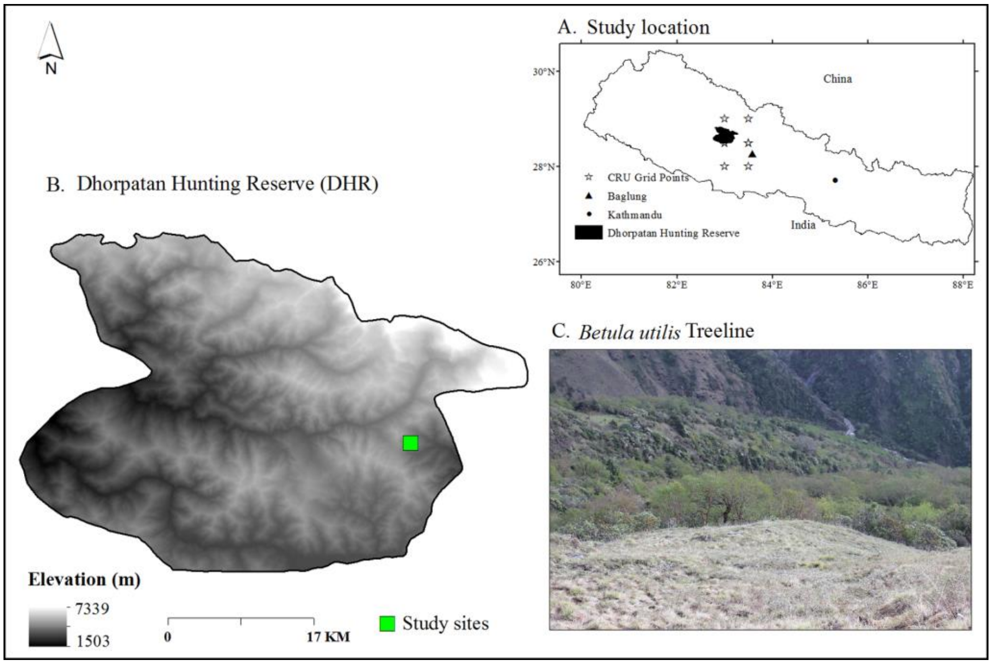
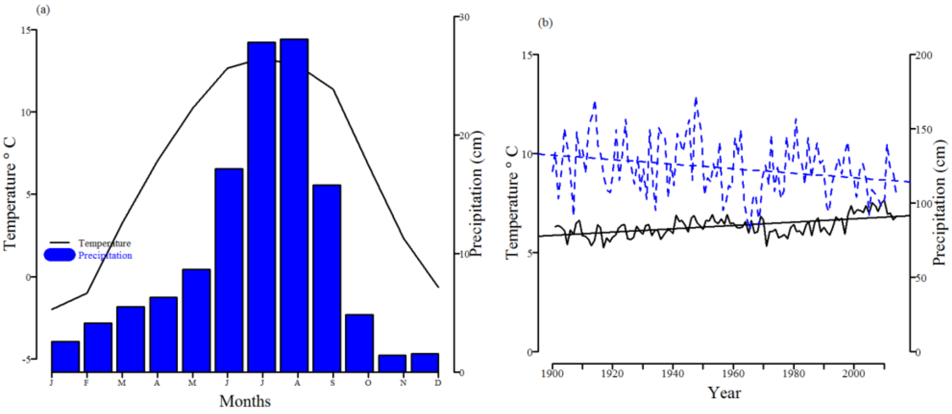


Figure 4-1: Study area. (A) Inset map showing location of Dhorpatan Hunting Reserve (DHR), nearby district headquarter (Baglung), CRU grid points location, and Nepal capital city (Kathmandu); (B) Map showing DHR elevation zone and study site in right-middle part; (C) Field photograph of treeline of *Betula utilis* from study site.



Seasonal trend

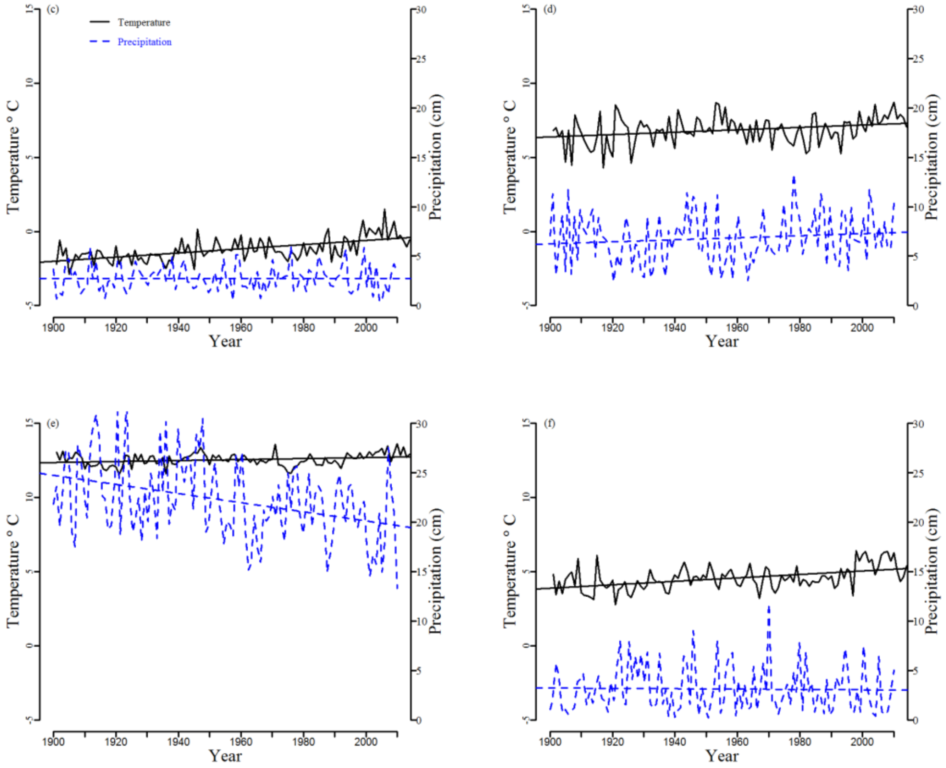


Figure 4-2: Climate of the study area. (a) and (b) showing average monthly temperature and precipitation trend of the region. (c) - winter, (d) - spring, (e) - summer, and (f) - autumn showing seasonal temperature and precipitation trend.

Field method

A topographically uniform area was identified in the field to establish two transects on a northeast facing slope. First, the forestline was identified in the field based on 30% canopy cover in a 20 x 20 m sq area (Chhetri and Cairns, 2015). Then a 20 m wide transect was extended 100 m above the forestline and 20 m below the forestline. Geographic coordinates of the four corners of the transects were recorded using a Garmin GPS map 78 handheld unit (accuracy 3–5 m). Zhang et al. (2009) suggested that forest around the treeline may be more responsive to global warming than at the treeline alone, so I extended our transect 20 m below the forestline. The origin for each transect (x, y = 0, 0) was located at the lower left side of the transect facing the upslope. The location of each individual within the transects was recorded at the center of the stem to analyze the spatial point pattern of individuals distributed.

All the individuals of *B. utilis* within the transects were enumerated and classified into three height classes: trees (> 2 m), saplings (0.5–2 m), and seedlings (< 0.5 m). All the individuals of *B. utilis* within the transects were mapped (latitude, longitude, elevation), and morphometric features (height, diameter at breast height [DBH]) were measured. For the trees, DBH was measured at 1.3 m aboveground using a diameter tape. A clinometer was used for measuring the height of trees > 2 m, and a measuring tape was used for measuring the height of individuals < 2 m. A total of 68 (45 for A, and 23 for B) trees were sampled and mapped; among these, six trees were dead.

Tree-ring cores from the base of each tree were collected using an increment borer to determine the age. The age of the 90 seedlings and 15 saplings was determined using the whorl count method (Chhetri and Cairns, 2015; Gaire et al., 2016). To check the accuracy of the whorl count, 16 cut samples (10 seedlings and six saplings) were also collected.

Laboratory method

Collected tree-ring cores were air dried at room temperature and mounted in wooden frames. A belt sander was used to enhance the visibility of the tree ring. Pith was missing from 10% of the samples and corrected using the curvature of the innermost ring (Speer, 2010). Tree-ring cores were cross-dated using visual cross-dating by matching patterns of relatively wide and narrow rings to remove false and missing rings (Fritts, 1976; Gaire et al., 2017). A spaghetti plot (ring width pattern) generated from the Program Library in R (dplR) software was also used for the visual cross-dating (Bunn, 2008).

Age structure, recruitment pattern and density

Stand dynamics were analyzed by classifying individuals into 10-year age classes. Decadal age-class frequency distribution helps to reduce dating error (Trant and

Hermanutz, 2014). Age structures were developed separately for above- and below-forestline individuals. The density of seedlings, saplings, and trees above and below the forestline was calculated to see the regeneration trend. For calculation of the density, only the first 20 m of the transect length was considered above the forestline, instead of the 100 m surveyed length, in order to stay consistent with the 20 m below-forestline length surveyed.

Spatial pattern analysis

Spatial pattern analysis was carried out to see whether the distribution pattern of individuals within the transect is completely random, clustered, or regularly distributed. I used the Ripley's K(t) statistical method to determine the spatial pattern in establishment (Elliott, 2011; Ripley, 1977). I converted K(t) into L(t) by applying a square-root transformation (Elliott, 2011; Ripley, 1977):

$$L(t) = [K(t)/\pi]^{1/2} - t$$

where t is the distance between individuals based on Euclidean measurement. The function $L(t)$ stabilizes its variance and has an expected value of approximately zero under the Poisson assumption (Lingua et al., 2008). The spatial pattern is defined as clustered, random, or uniform if the L(t) values are greater than, equal to, or lower than the confidence envelopes, respectively (Lingua et al., 2008).

RESULTS

Treeline ecotone and morphometry

The *Betula utilis* forest extends from the river valley at 3500 m to about 3900 m in the Rugakharka area of DHR, Western Nepal. The forestline of *B. utilis* was observed at 3897 m and 3890 m in Transects A and B, respectively. The treeline was observed at around 3905 m and 3891 m in Transects A and B, respectively. No seedling or sapling was observed above the treeline in Transect A, and the uppermost sapling was observed at 3895 m in Transect B, which is also the species limit (Table 4-1 and Figure 4-3). The *B. utilis* treeline stands are young, with the average age of trees being 53 years and 62 years in Transects A and B, respectively. The oldest individual was 129 years old in Transect A. Age/elevation, DBH/elevation, and height/elevation relationships indicated that age, DBH, and height do not decrease with increasing elevation (Figure 4-4). A deep moss layer was absent above the forestline area in both the transects. Seedlings and saplings below the forestline were observed in areas covered by moss with litter. Seedlings were emerging from a moss layer. A significant part of the seedlings were under the moss. Ten seedlings uprooted for sampling indicated that about 45% of the total height was under the moss cover. Due to the thick moss layer, seedlings 1–5 years old were not observed or were not visible. Our seedlings counts are therefore likely conservative estimates of the number of seedlings present.

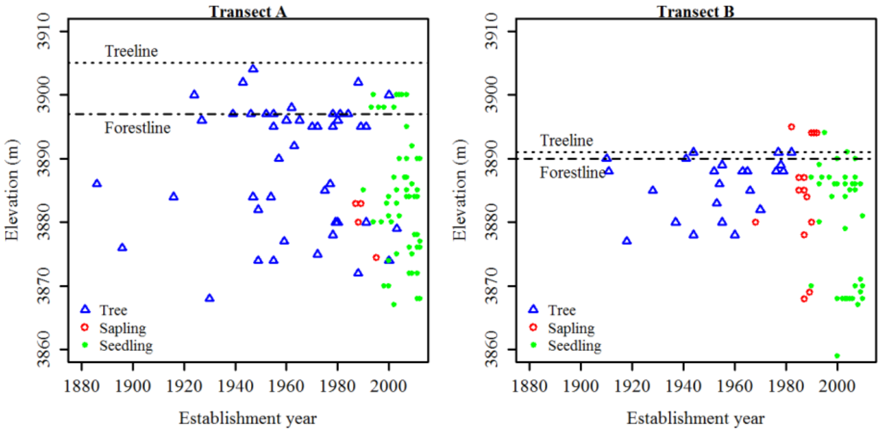


Figure 4-3: Spatio-temporal variation in recruitment of *Betula utilis* in study transects.

Table 4-1 Description of the study transects

	Transect A	**Transect B**
GPS coordinates	28.5510N, 83.1748E	28.5513 N, 83.1742E
Average slope (º)	38	37
Forestline (m)	3897	3890
Treeline (m)	3905	3891
Species limit (m)	3905	3895

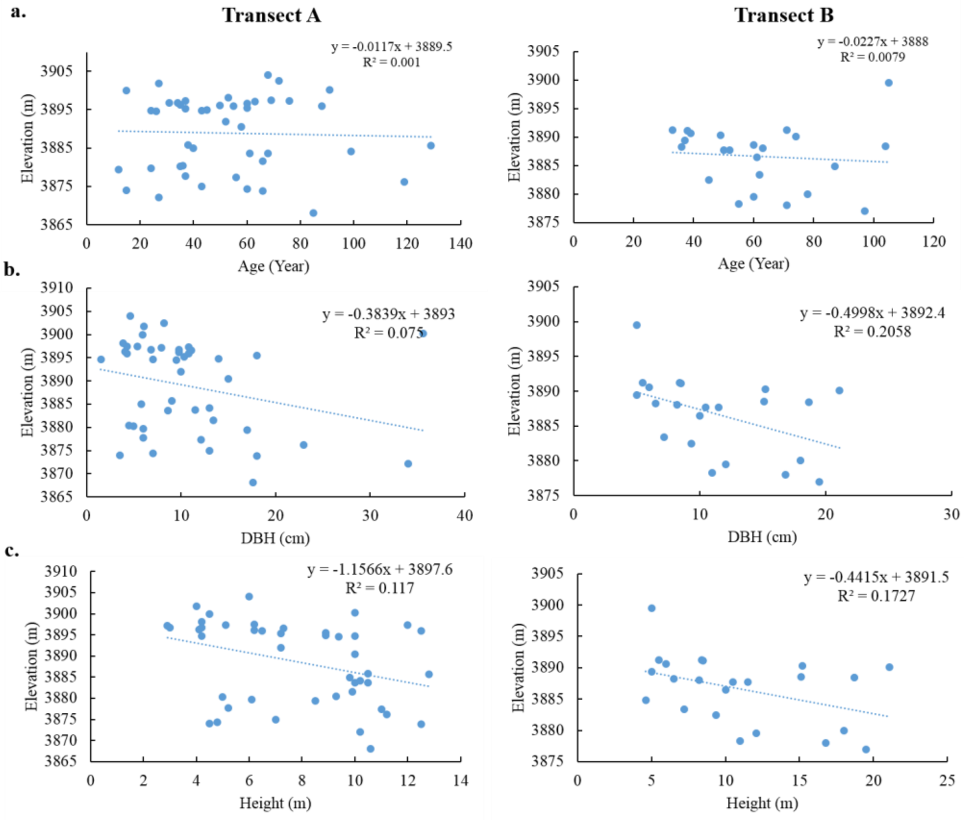


Figure 4-4: Elevation and morphometric relationship. a. elevation and age, b. elevation and DBH, c. elevation and height.

Age structure, recruitment pattern, and density

The age structure curves derived for the below-forestline site in both transects were nearly reverse J-shaped (Figure 4-5). No clear reverse J-shaped age structure curve was noted for the above-forestline area. Most of the individuals in Transect A and all the individuals in Transect B were established after 1900. Poor regeneration was observed above the forestline (Figures 4-3 and 4-5). Saplings were absent above the forestline in Transect A. In Transect A, no seedlings or saplings were observed above the forestline, but in Transect B, there were a few seedlings and saplings present above the forestline. A significant number of seedlings and saplings were recorded below the forestline in both transects (Figure 4-3 and Table 4-2).

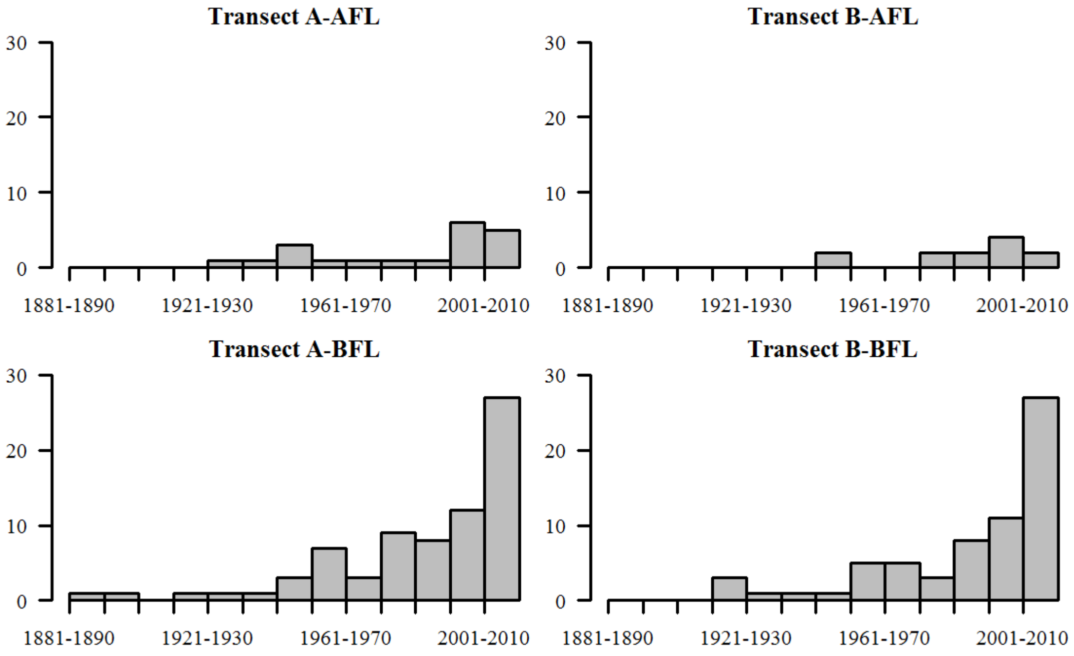


Figure 4-5: Age structure of *Betula utilis* above (AFL) and below forestline (BFL).

Table 4-2 Density of seedling, sapling, and tree below forestline (BFL) and above forestline (AFL)

Density (Stems/Hectare)	**Transect A**		**Transect B**	
	BFL	**AFL**	**BFL**	**AFL**
Tree	875	250	475	100
Sapling	100	0	250	175
Seedling	1175	275	950	125

Spatial pattern analysis

The most recently established individuals (seedlings and saplings) were concentrated near the lower elevation of both transects (Figure 4-6). The spatial distribution pattern of seedlings and saplings in the transect suggests that they were establishing away from the canopy of the likely parent trees. In Transect A, L(t) values were greater than the confidence envelopes for both trees (after 1.5 m distance), and seedlings and saplings suggested clumping (Figure 4-7). In Transect B, the L(t) value for trees was within the confidence envelope, so trees were not clumped. On the other hand, the L(t) value distribution suggested clumping for seedlings and saplings (Figure 4-7).

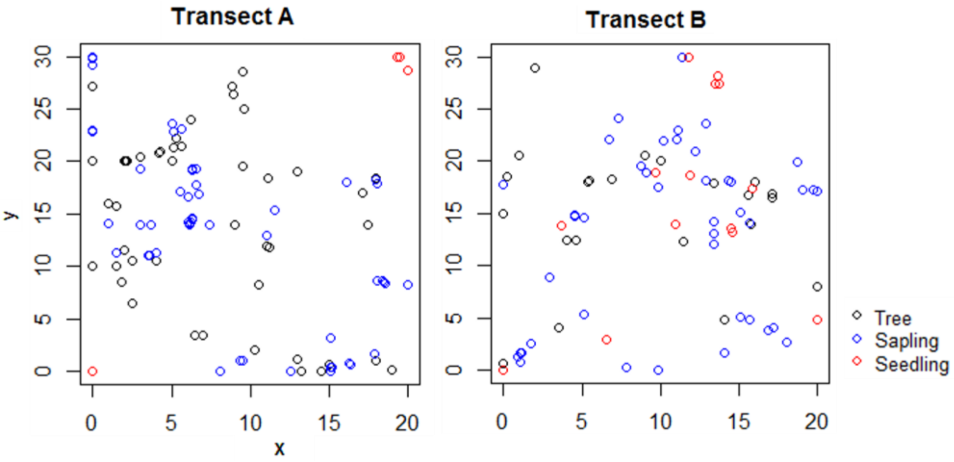


Figure 4-6: Spatial pattern of Betula utilis individuals within Transects A and B. Individuals are grouped into three classes (trees, saplings, and seedlings). The y-axis is along the elevational gradient and covers 20 m below the forestline and 10 m above the treeline of entire transect (120 m * 20 m).

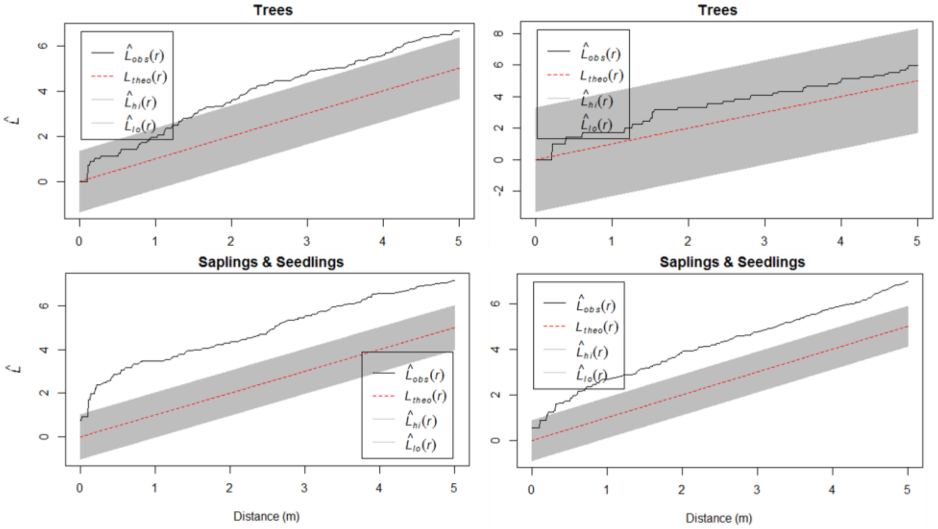


Figure 4-7: Ripley's K(t) for the trees, saplings, and seedlings combined in two transects. The gray area is the confidence envelopes (99%). The square-root transformation, L(t), was applied.

DISCUSSION

The observed forest is characteristic of a young stand; the stand age is less than 100 years. Similar young stands of *B. utilis* and other species were recorded from other treeline sites in the Nepal Himalayas (Gaire et al., 2016). *Betula utilis* is the dominant species around the treeline ecotone in the Dhorpatan region and forms an abrupt treeline; this observation was similar to findings by Gaire et al. (2014) in the Manasulu region and Shrestha et al. (2007) in the Manang region. The *Betula utilis* treeline in DHR is not advancing because the potential for upward migration of the treeline would be evidenced by an abundance of seedlings and saplings above the treeline (Mathisen et al., 2014). Here, such abundance is lacking. The lack of a significant relationship between age/elevation, DBH/elevation, and height/elevation also suggests that the treeline is not advancing in response to climate warming. Treeline formation is associated with its sensitivity to climate warming, and diffuse treelines are more sensitive than abrupt (Harsch and Bader, 2011). It is therefore possible that form is the reason that the treeline in this area is not advancing.

The low number of young individuals above the forestline indicates that infilling of the treeline ecotone and treeline advancement has not been occurring in the last few decades in this area. The reverse J-shaped age structure below the forestline indicates that the forest is regenerating. However, regeneration above the forestline is poor and insufficient to trigger treeline advance. Forest regeneration or recruitment at the treeline ecotone is influenced by viable seed production, seed dispersal limitation, and seedling competition with ground vegetation (Wallentin et al., 2008). The presence of many seedlings and saplings below the forestline suggests that seed production is not the limiting factor here. *Betula utilis* seeds have wings that help in wind dispersal (Moen et al., 2004), so dispersal is not the limiting factor. Moreover, many studies, such as Zhang and Fang (2004) and Ren et al. (2015), have reported that *B. utilis* produce high seed yield, so I do not consider seed production to be the limiting factor.

One of the factors that leads to differences in above- and below-forestline seedling and sapling density is related to moss and litter. Good regeneration below the forestline is due to litter and moss layer cover. This layer helps to trap the moisture for a longer time and helps to regenerate seeds. This layer also provides immediate shelter from solar radiation. High solar radiation can lead to fatal seedling desiccation (Germino et al., 2002). Therefore, a suitable microsite for *B. utilis* seedling regeneration would have moss cover and herbaceous cover to protect it from sunlight and provide moisture. On the contrary, in the DHR, the area above the forestline is devoid of litter and moss layer. In fact, the area above the forestline is mostly covered by Buki (Tussock grass). In this open area, seedlings are exposed to high solar radiation and to low overnight temperatures and nighttime sky, thus putting seedlings in a more disadvantageous position than Tussock grass (Germino and Smith, 2000; Maher and Germino, 2006). Low *B. utilis* recruitment was also observed in the treeline area of Langtang, Manasulu, and Sagarmatha (Liang et al., 2014). Liang et al. (2014) pointed out that low regeneration and the stable treeline of *B. utilis* is due to increasing moisture stress because the *B. utilis* treelines of the Himalayas are drought influenced. An increasing temperature trend and decreasing precipitation trend may create drought stress on younger individuals of *B. utilis* in the Dhorpatan region. Consequently, there is a chance that low moisture availability is responsible for low recruitment above the forestline.

There should be a spatial pattern of seedling establishment below the forestline because Shrestha et al. (2007) and Hughes et al. (2009) found that seedlings of *Betula spp.* could not establish under their own closed canopy. Low light and thick litter under the canopy may prevent seedling establishment (Shrestha et al., 2007). I also observed that most of the seedlings and saplings were established away from the canopy of *B. utilis,* but only in areas covered by moss that ensure moisture needed for germination and seedling establishment. This indicates that there is some level of moss cover that balances protection in the absence of the negative effects of too much moss cover. The importance of moss in the seedling establishment of *Picea crassifolia* on the Qilian mountain in the Tibetan plateau (Wang et al., 2017) and for other species in the study area is highlighted by similar finding from other treeline dynamics studies. Spatial pattern analysis suggests clustering of seedlings and saplings away from the canopy of the big trees. Clumping of seedlings and saplings suggests a requirement of microsites for their establishment. Local microsite heterogeneity in both transects possibly contributed to the clumping in seedlings and saplings (Wang et al., 2012). Clumping in the case of younger individuals was also recorded in other species (Chen et al., 2010;

Wang et al., 2012). The clumping in seedlings and saplings being much stronger than that observed for adult trees suggests that microsites are more important for the establishment of juveniles but that eventually competitive processes will result in the death of closely established trees.

As in Barun Valley, Eastern Nepal (Chhetri and Cairns, 2015), and Rolwaling Himal, Central Nepal (Schwab et al., 2016), dense *Rhododendron campanulatum* shrubs are absent in Dhorpatan, so dense shrub cover can be ruled out as a factor in preventing recruitment. There are two possibilities that can account for the absence of recruitment above the forestline. One is the lack of microsites (thick moss cover with litter), and the other is the presence of herbivores above the forestline. The edge of the subalpine *B. utilis* forest in the Dhorpatan area is the main grazing site for domesticated sheep and wildlife (blue sheep). I observed signs of browsing on seedlings and saplings above the forestline. Browsing in the treeline area prevents regeneration, and, in areas of intense browsing, very few saplings and young trees would be found above the forestline (Moen et al., 2004; Speed et al., 2010). The presence of browsers above the forestline would prevent the treeline's upward movement due to the browsers feeding on seedlings and saplings already weakened by adverse climatic conditions and competition from field layer plants (Moen et al., 2004). The palatability of field layer vegetation (Tussock grass) above the forestline is higher than below-forestline vegetation (Rhododendron). Therefore, the area above the forestline is more affected by herbivory than the area below the forestline. This is an alternative explanation for the presence of more seedlings and saplings below the forestline. These disturbances caused by herbivores and the lack of microsites override the effect of warming. Therefore, there is little potential for any treeline advance in this area in the future until herbivore husbandry is ceased, and suitable microsites develop.

CONCLUSIONS

Betula utilis forms the abrupt treeline in DHR, Western Nepal, and very few individuals are present above the forestline. In spite of the increasing temperature trend, low regeneration at the treeline ecotone suggests that site-specific biotic and abiotic factors are controlling the treeline dynamics. Seedling establishment above the forestline is limited by a lack of moisture, absence of suitable microsites, and presence of herbivores. To properly investigate the effect of herbivores at the treeline, enclosure experiments are needed. Similarly, the open sky exposure effect can by studied by creating artificial disturbances or canopy cover above the treeline or by transplantation in a controlled area.

CHAPTER V

CLIMATE CHANGE DRIVES TREELINE ADVANCE IN THE NEPAL HIMALAYA

INTRODUCTION

Mountain plant communities are sensitive to climate driven range shifts (Telwala et al., 2013). As treeline ecotones invade high elevation, alpine tundra biomes shrink or shift upslope. Previous work has shown treelines are distributionally linked to temperature (Gehrig-Fasel et al., 2007; Körner, 2012), with new trees prevented from establishment at higher elevation by short growing seasons or belowground permafrost limiting root establishment. As climate has warmed, many treelines around the planet have shift upward (Gaire et al., 2014; Greenwood and Jump, 2014; Harsch et al., 2009). Nevertheless, not all sites have responded the same, with some species and regions remaining stable or actually retreating (Harsch et al., 2009). Within regions already threatened by habitat change, estimating the degree to which future climatic shifts may influence treeline habitat suitability is essential for both scientific understanding and conservation planning. Tundra lost to treeline expansion (Moen et al., 2004) reduces the habitat for endangered tundra species. For instance, the endangered snow leopard in the Himalayas could lose as much as 30% of their habitat under future warming scenarios and observe an increase in competition from other cat species (Forrest et al., 2012;

Lovari et al., 2013). This combination of factors has the potential to severely reduce Himalayan biodiversity.

Species Distribution Modeling (SDM) provides a baseline for predicting a species response to climate change (Hernandez et al., 2008). SDM is an emerging toolset that examines the relationship- between species distribution and landscape variables to map habitat suitability for a species in a region (Shrestha and Bawa, 2014). This model can be used to determine if other regions might support a species today and also use predictions of future landscapes to map how habitat suitability for a species may change in the future (Randin et al., 2009). SDM helps elucidate the niche requirements of a particular species (i.e., the Hutchinsonian environmental niche), which may assist in the development and assessment of conservation efforts. There are several existing approaches to SDM (e.g. DOMAIN, Maxent, and GARP) that vary in model construction and assumptions (Elith and Graham, 2009). Of these, Maxent performs better than other programs when using small sample sizes, operates with presence only data, and avoid error prone absence records (Ellith et al., 2006; Kumar, 2012; Pearson et al., 2007). In addition, Maxent provides a continuous surface output that distinguishes between areas with greater or lesser predictive certainty (Phillips et al., 2006). Previous analysis has found the software to provide reasonably good estimates of species range shifts with climate change (Hijmans and Graham, 2006). Recently, this approach has been applied to gain a better understanding of treeline dynamics in response to warming and to understand existing process-pattern relationships (Schickhoff et al., 2015).

The Himalayas contain an expansive area of understudied treeline habitat that is likely to respond to ongoing climate change. The Himalayas contain a high altitudinal gradient, complex topography, high warming rate, biodiversity hotspots, and close proximity to indigenous communities (Xu and Grumbine, 2014). These features make the Himalayas a unique environment where treeline related studies carried out elsewhere cannot be generalized. Therefore, studies focusing on the distribution of treeline species in the Himalayas are needed to understand and conserve Himalayan ecosystems (Singh et al., 2013). Previous studies of treeline in this area have indicated mixed treeline response to climate change over a limited area (Chhetri and Cairns, 2015; Gaire et al., 2014; Shrestha et al., 2014; Suwal et al., 2016). The degree to which these trends scale up to broader patterns remains unresolved. Modeling approaches to identify contemporary climatic limits of Himalayan treeline species ranges and predict distributions under alternative future climatic regimes have not yet been conducted (Schickhoff et al., 2015). Recently, modeling studies of the environmental niches of *Betula utilis* in Uttarakhand, India (Singh et al., 2013) and the Himalayan range (Schickhoff et al., 2015) have been carried out, both indicating potential habitat shift. We wish to add to this knowledge, examining representative Himalayan species to gauge the future of this region.

In this study, I used species distribution modeling to determine if the distributions of three common Himalayan treeline forming species are defined by climate and predict if their ranges are likely to expand or contract under alternative climatic regimes through an increase or decrease in suitable habitat. The study area is the country of Nepal, which covers the majority of the Himalayan range and has observed significant shifts in climate within the last 50 years (Shrestha and Devakota, 2010). The three study species, *Abies spectabilis* (D. Don), *Betula utilis* (D. Don), and *Pinus wallichiana* (A. B. Jacks), are important components of the Nepalese sub-alpine ecosystem and are dominant within the Nepalese Himalayan treeline (Chhetri et al., 2017). I address two questions: 1) which topo-climatic variables best explain the distributions of Himalayan treeline forming species in Nepal? To answer this question I examined the relationship between the contemporary distributions of my study species with the underlying climatic (19 variables) and topographic variables (five variables) that define each location. 2) Will the distribution of Nepalese treeline forming species likely expand or contract under future climatic shifts? I examine how habitat suitability of the three study species will shift under three alternative future climate scenarios within the Nepalese Himalayas and compare the elevational range of future suitable habitat to contemporary distribution.

MATERIAL AND METHODS

Study area

Analysis of climate records has indicated that temperature in the Nepalese Himalayas is increasing at a higher rate relative to other mountains of the world, especially since the 1950s (Shrestha and Devkota, 2010). This warming has progressed at a steady rate since the mid-1970s and is more pronounced at higher elevation. In addition, precipitation has increased by 13 mm per year on average while the number of rainy days has decreased by 0.8 days per year, suggesting more intense rainfall (Shrestha et al., 2000). These changes not only threaten the large stores of fresh water in the form of ice and glaciers at high elevations in the Himalayas, but also threaten the plant and animal life native to this area. Several climate models (CIMP 5, LARS-WG, PRECIS HadCM3, and RegCM3) have predicted a steady increase in temperature throughout Nepal accompanied by a decrease in monsoon rainfall in the north and an increase in the south (NCVST, 2009; Shrestha and Aryal, 2010).

Species selected for the modeling

Abies spectabilis (D. Don), *B. utilis* (D. Don), and *P. wallichiana* (A. B. Jacks) are dominant treeline species in the Nepalese Himalayas (Chhetri et al., 2017). *Abies* *spectabilis* (Himalayan silver fir) is a tall pyramidal evergreen tree growing in the sub-alpine forests of the Himalayas. It is found within the elevational range of 2800–4000 m in Nepal (Ghimire and Lekhak, 2007; Stainton, 1972). This tree is characterized by low branching with dense foliage. At the upper limits of its elevational range, it is usually associated with *B. utilis* and *Rhododendron spp*. The sub-alpine *A. spectabilis* forest is a unique habitat for the endangered *Ailurus fulgens* (Red panda). *Betula utilis* (Himalayan birch) is a plant native to the Himalayan region and is found across an elevational range of 2700–4500 m. It grows up to 20 m in height and grows among scattered conifers such as *A. spectabilis* and *P. wallichiana* with an undergrowth of shrubs such as evergreen *Rhododendron spp*. This tree grows in moist areas of the Himalayas, particularly in gullies where the snow remains into the late spring and summer. *Betula utilis* composes treeline vegetation throughout the Nepalese Himalayas and dominates among broadleaved angiosperm tree species in the Himalayas at sub-alpine elevations (Shrestha et al., 2007). *Betula utilis* forests are a habitat of the endangered *Moschus chrysogaster* (musk deer). Blue pine (*P. wallichiana*) is an evergreen conifer found in the Himalayan region from 1800–4200 m (Ghimire et al., 2011). This tree is generally found in valleys and foothills, occasionally in pure stands but often in association with other species such as *A. spectabilis* and *B. utilis*. *Pinus wallichiana* prefers a drier environment than *A. spectabilis* and *B. utilis*, and therefore its distribution is primarily concentrated in the drier central and western parts of Nepal. *Pinus wallichiana* is an important source of timber and fuel for villagers in mountain valleys and is also important part of the mountain ecosystem (Ghimire et al., 2011). The sub-alpine zone occupied by these species in the Nepalese Himalayas is a center of agropastoralism, making it highly prone to additional disturbance that may exacerbate climate induced shifts in this area.

Species occurrence data

I gathered species occurrence data from several sources: my field surveys carried out in different parts of Nepal (2004 – 2011), distribution records in previous literature, the Global Biodiversity Information Facility (http://www.gbif.org), and the Flora of Nepal database (http://www.padme.rbge.org.uk/floraofnepal/index.php?page=home). I checked herbarium records for georeferencing error, misidentification, and duplication with field survey and records collected from the published literature. I only included records collected after 1980 in my analysis to reduce potential error related to geographic coordinate accuracy. I used a total of 240 records for modeling: 94 for *A. spectabilis,* 85 for *B. utilis,* and 61 for *P. wallichiana* (Figure 5-1). Presence records were included in the model to increase the spatial extent of the study area.

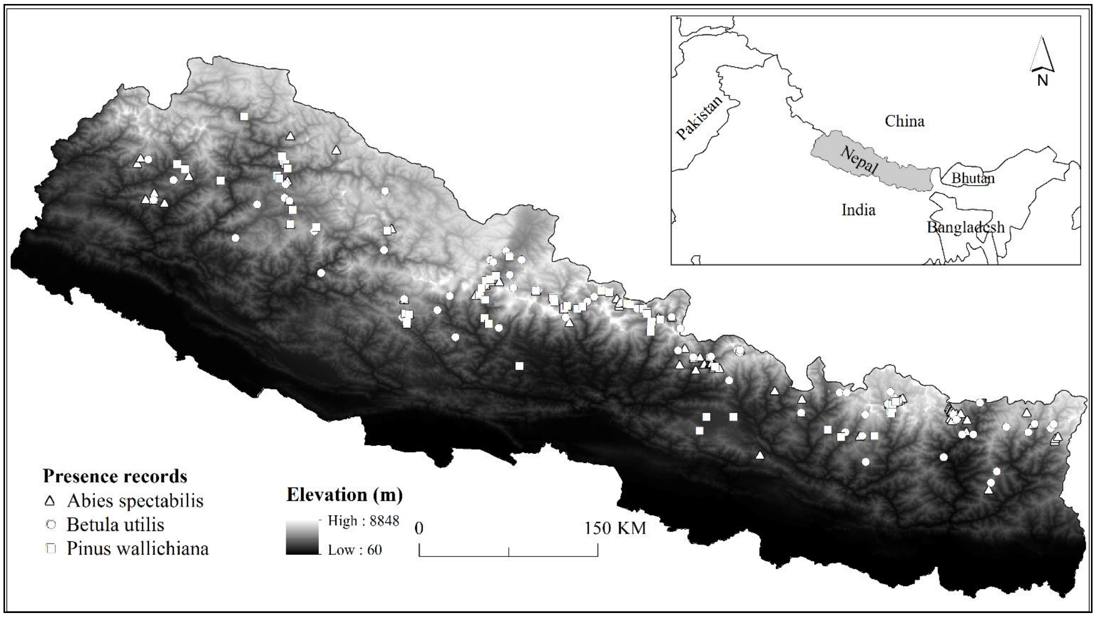


Figure 5-1: The distribution records of *Abies spectabilis* (94 records), *Betula utilis* (85 records), and *Pinus wallichiana* (61 records) collected from GBIF, Flora of Nepal, locations identified in previous publications, and field survey.

Topo-climatic variables

To examine spatial climatic variation within the study area, I gathered nineteen bioclimatic variables with a 30 arc second (~1 km) spatial resolution from the WorldClim - Global Climate Data (http://www.worldclim.org) (Hijmans et al., 2005) (Appendix I). Additionally, I determined the topographic characteristics of Nepal (eastness, elevation, northness, topographic position index (TPI), solar illumination index (SII)) from the ~1 km spatial resolution Digital Elevation Model (DEM) obtained from Diva GIS (http://www.diva-gis.org/ (Oke and Thomposon, 2015; Weiss, 2001)). Eastness (sine of aspect) and northness (cosine of aspect) are the linear component of aspect. TPI is the measure of surface undulation that allows an area to be classified both as its topographic position (e.g. ridge top, valley bottom, mid-slope) and landform category (e.g. gentle valleys, plains, steep narrow canyons, open slope). SII approximates the amount of direct solar radiation that hits an area as a function of its aspect, slope, and elevation. I included these variables in the model to account for variation in environmental conditions, such as solar radiation, soil moisture, and snow cover (Carlson et al., 2013).

I removed redundant climatic or topographic variables from my analyses that were highly correlated (Pearson correlation coefficient (r) greater than 0.9) with other variables. This resulted in ten variables: isothermality (quantifies how large the day to night temperatures oscillate relative to the summer to winter (annual) oscillations), annual temperature range, mean temperature of the coldest quarter, precipitation of the driest month, precipitation seasonality, precipitation of the warmest quarter, precipitation of the coldest quarter, eastness, northness, TPI, and SII (Appendix II). I retained elevation in spite of its high correlation with other variables because elevation has significantly improved the predictive ability of SDM models for other high elevation plant species (Oke and Thomposon, 2015), and elevation is considered an important determinant of species distributions in mountain habitat (Körner, 2012).

I obtained data for three downscaled future global climate models (GCM) from the Coupled Model Intercomparison Project Phase 5 (CMIP5, IPPC Fifth Assessment) from the Consultative Group on International Agriculture Research (CGIAR)'s Climate Change, Agriculture and Food Security (CCAFS) climate data archive (http://www.ccafs-climate.org/), and the Global Coupled Atmosphere-Ocean General Circulation Model (BCC-CGCM1.0) developed by the Beijing Climate Center. These models are based on the IPCC fifth assessment report (AR5) that modeled greenhouse gas emission trajectories, called Representative Carbon Pathway (RCP). The first, RCP 2.6, is based on a reduction in greenhouse gas concentration (hereafter lowest emissions). According to this lowest emissions scenario, global annual greenhouse gas emissions peak in between 2010 – 2020, and temperatures are projected to increase in range 0.3 – 1.7 °C. The second, RCP 6.0, is based on a stable greenhouse gas concentration (hereafter stable emissions). Stable emissions assume that emissions peak around 2080 and then decline, with temperature increasing by 0.8 – 3.1 °C. The last, RCP 8.5, proposes an increase in greenhouse gas concentration (hereafter highest emissions). Highest emissions assume greenhouse gas emissions continue to increase throughout 21st century, with temperature increasing 1.4 – 4.8 °C by 2100. For each model, I examined the predicted future climate under each scenario at two different time periods (2050 and 2070). The 2050 time period is average for 2041 – 2060, and 2070 is average for 2061 – 2080 period. The supplementary table S3 indicates climatic range and mean values in current and forecasted scenarios.

Species distribution model

I used the maximum entropy (Maxent) software version 3.3.3k (Phillips et al., 2006) to conduct species distribution modeling. Maxent uses a machine learning process that estimates the habitat suitability of a species in an area based on the association between landscape variables and known distribution records (Kumar and Stohlgren, 2009). The Maxent model works well with presence only data (Elith et al., 2011) and is capable of identifying contemporary and future habitat suitability under alternative climate scenarios (Hijmans and Graham, 2006). This generates an indication of a species likelihood to expand or contract its range if new habitat is likely to become available or occupied habitat is likely to become unsuitable. It is less sensitive to sample size than other SDM packages (Wisz et al., 2008) and is one of the most popular SDM programs, with more than 1500 published applications since 2006 (Merow et al., 2013).

I ran my Maxent analysis using the following parameter values in my simulations: random test percentage, 30%; regularization multiplier, 1; maximum number of background points, 10000; maximum iterations, 5000 or until convergence; convergence threshold, 0.00001; and crossvalidated replicated run type. I set the model to remove duplicate presence records at the spatial resolution of the topo-climatic variables (Soria-Auza et al., 2010), so that I included only one presence record within the ~1 km^2 grid cell for each species. I ran 15 replicates for each species and averaged the results. The program created background data by using known occurrence points. I used a Jackknife test to measure the performance of topo-climatic variables in the model, reporting the importance in explaining the species' occurrence and the quantity of unique information each variable provides (Baldwin, 2009). I used the omission and predicted area curve and area under the receiver operating characteristic curve (AUC) to assess the quality of the model (Fielding and Bell, 1997). The omission and predicted area curve is a threshold-dependent binomial test that compares the extrinsic omission rate to the proportional predicted area, where close fit of the two measure indicates a good fit. The extrinsic omission rate is the proportion of known species occurrence locations withheld from the model construction that fall into pixels where the model predicts the habitat as being unsuitable to a species and should be a lower value in a good model. The proportional predicted area is the fraction of all the pixels that are predicted as suitable for the species (Phillips et al., 2006). The AUC is commonly used to assess model fit in the Maxent literature, and it represents the probability that a known occurrence locality will be classified as more suitable than a random background point (Gallardo et al., 2015; Merow et al., 2013). An AUC value of 0.5 – 0.7 indicates a poor model fit, an AUC value of 0.7 – 0.9 indicates a moderate model fit, and an AUC value > 0.9 indicates a good model fit (Franklin, 2010; Shrestha and Bawa, 2014). The final raster product for the study area contains pixel values between 1 (high habitat suitability) and 0 (low habitat suitability). I used a standard cutoff, where I assigned pixels with values greater than 0.5 as being suitable at that location (Kumar and Stohlgren, 2009; Porfirio et al., 2014). To determine if the distributions of Himalayan treeline forming species are primarily defined by climatic or topographic variables in Nepal (question 1), I compared the contribution of each climatic and topographic variable contributed to the final contemporary SDM.

To determine if habitat suitability of Nepalese treeline forming species are likely to expand or contract under predicted future climatic shifts (question 2), I compared the elevation and range area of the contemporary habitat suitability surface to that in the alternative future models. I estimated the total area of suitable habitat for the three species under current and future climatic conditions in ArcGIS 10.2 by using the raster to polygon and calculate geometry tools. I also calculated suitable habitat for each species as a fraction of the land area of the country of Nepal. To determine potential changes in the elevational distribution of treeline species, I extracted the elevation values of the pixels from the predicted and current distribution maps generated by the model using the DEM (Shrestha and Bawa, 2014). I converted the predicted occurrence and the DEM raster into polygons using ArcGIS 10.2. To determine if the elevation shifted significantly between the contemporary and three alternative future models for each species, I used an independent sample t-test to compare the mean elevation values of the suitable habitat under current and future climate scenarios (Shrestha and Bawa, 2014).

RESULTS

I developed SDMs for three study species on the basis of 240 presence records. Omission and predicted area curves indicated moderate to good model fit for the three study species (Figure 5-2). All of the observed omission rates on training samples and omission rates in test samples were close to the predicted omission rates. The models for all three treeline species performed better than random as indicated by the average test AUC values for the 15 replicate runs of *A. spectabilis* (0.89 ± 0.05), *B. utilis* (0.87 ± 0.05), and *P. wallichiana* (0.87 ± 0.06) (Figure 5-3).

The distribution of suitable habitat for the three treeline species under current climatic conditions is presented in Figure 5-4. My models indicate that present suitable habitat for *A. spectabilis*, *B. utilis*, and *P. wallichiana* cover 5130 km^2, 9822 km^2, and 9764 km^2, respectively. I have presented the area and percent of country covered in Table 5-1. The model also predicted that the most suitable habitat for *A. spectabilis* and *B. utilis* was in the eastern and central part of Nepal, and the most suitable habitat for *P. wallichiana* was in the central part of Nepal.

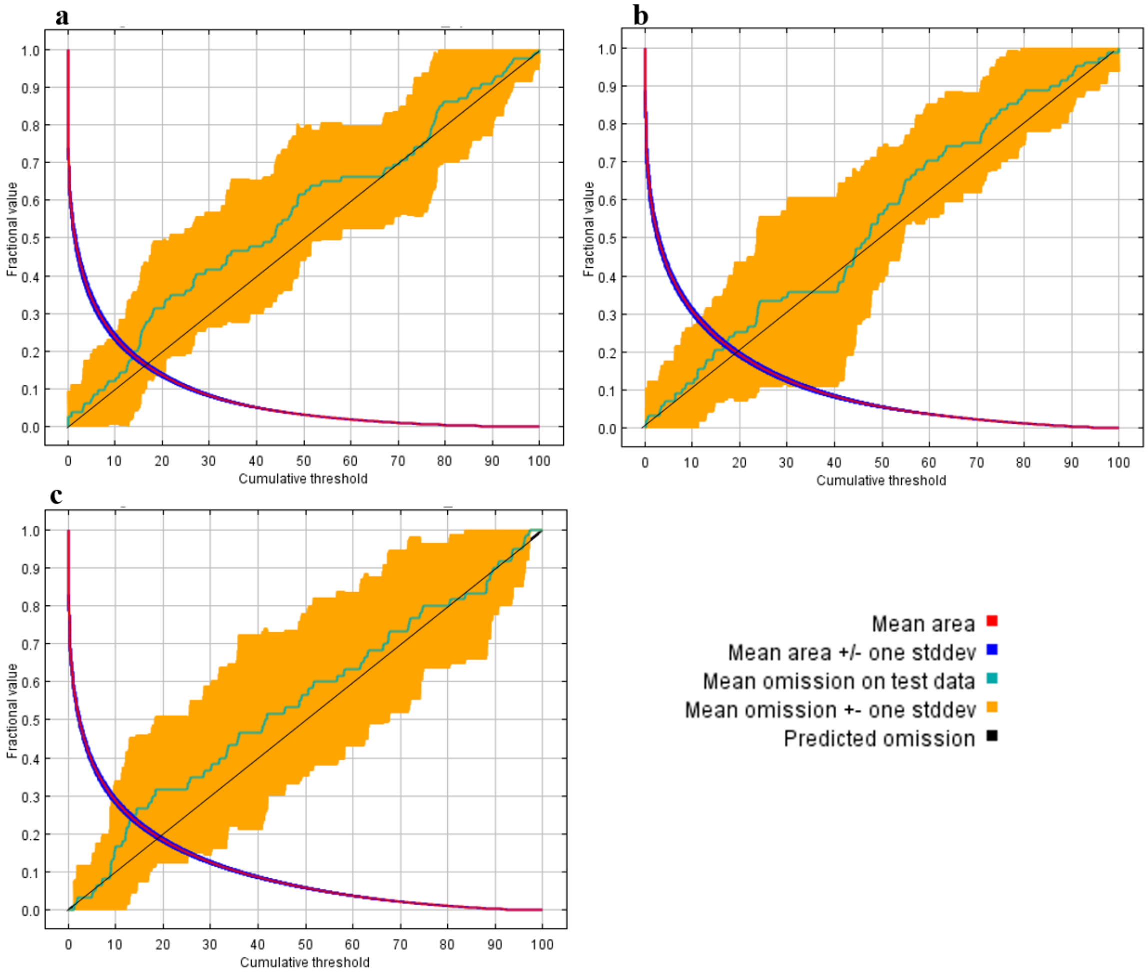


Figure 5-2: Omission and predicted area curves for (a) *Abies spectabilis*, (b) *Betula utilis*, and (c) *Pinus wallichiana*.

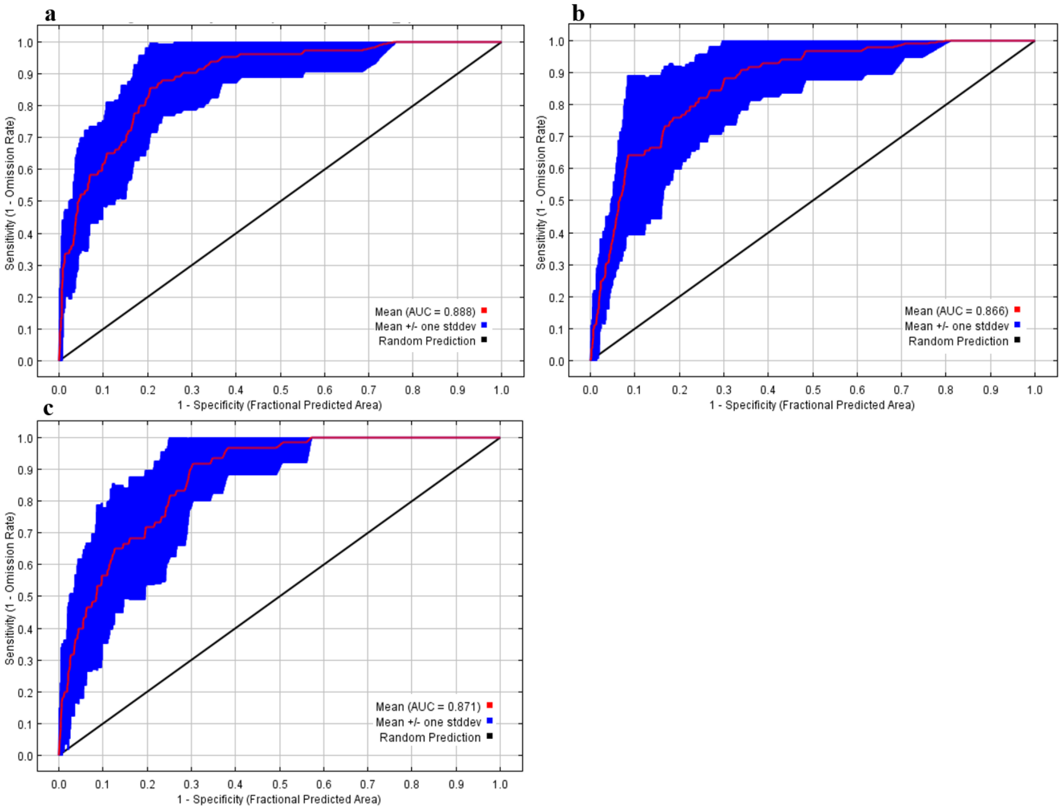


Figure 5-3: Area under the ROC curves (AUC) and AUC values for (a) *Abies spectabilis*, (b) *Betula utilis*, and (c) *Pinus wallichiana*.

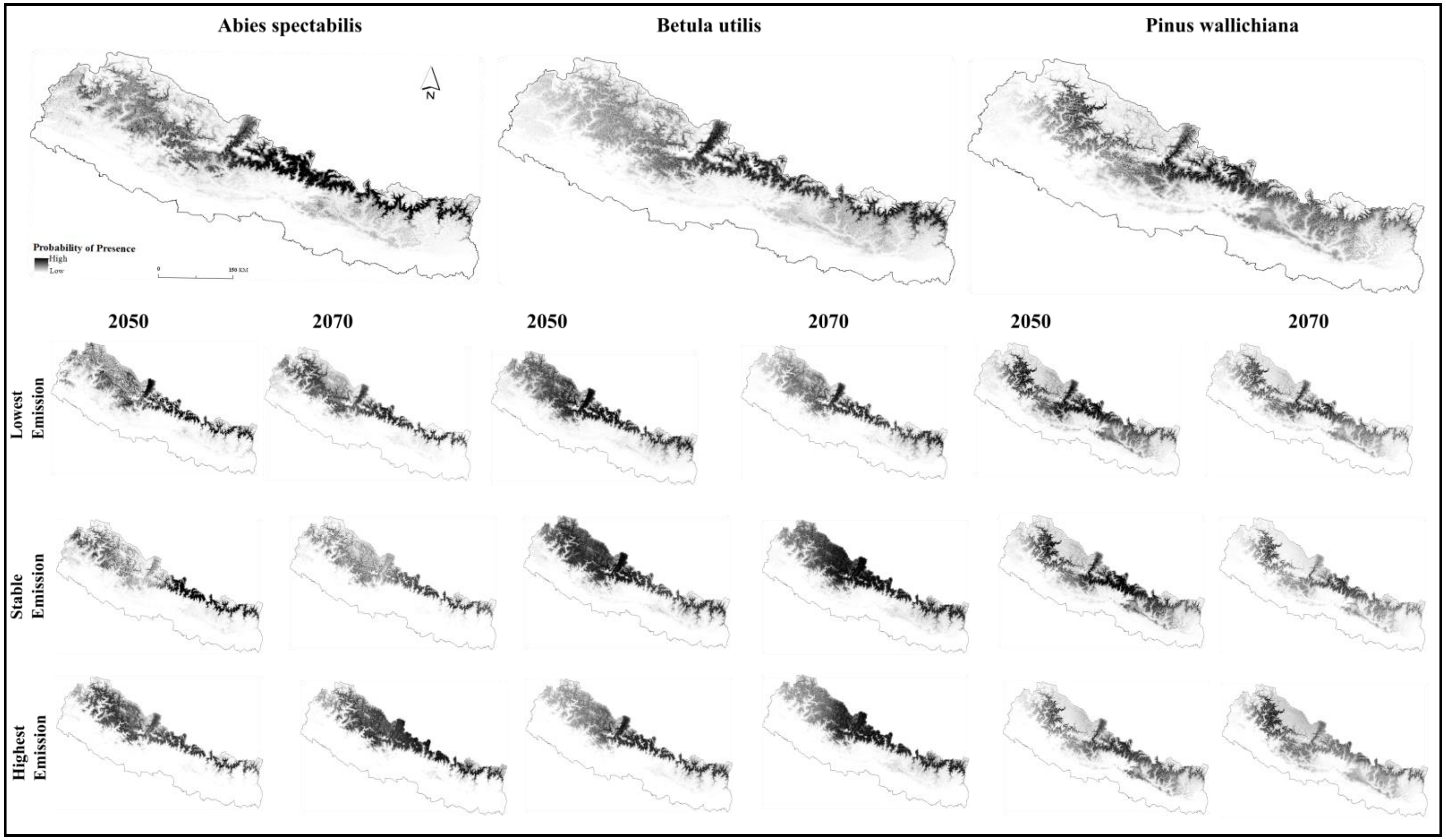


Figure 5-4: Suitable habitat for the three study species under current and future climatic conditions under three emissions scenarios (lowest, stable, and highest)

Table 5-1 Area with habitat suitable (habitat suitability > 0.5), measured as 1 x 10^2 km^2, for the three treeline species under current climate and the three alternative future climate change scenarios. Percent of Nepal with suitable habitat is within parentheses.

	Current	**Future climate change scenario**					
		Lowest emissions		***Stable emissions***		***Highest emissions***	
		2050	***2070***	***2050***	***2070***	***2050***	***2070***
A. spectabilis	51 (3.5)	100 (6.8)	178 (12.1)	44 (3.0)	90 (6.1)	217 (14.7)	279 (19.0)
B. utilis	98 (6.7)	206 (14)	129 (8.7)	360 (24.4)	363 (24.6)	156 (10.6)	266 (18.1)
P. wallichiana	98 (6.6)	117 (7.9)	96 (6.5)	117 (8.0)	51 (3.5)	114 (7.7)	92 (6.3)

A Jackknife test (Figure 5-5) indicated that for all three species elevation is the most important predictor of habitat suitability. The climatic variables isothermality and mean temperature of the coldest quarter were consistently important predictors for all three species. The percent of each variable to the final model is presented in Table 5-2. Elevation, isothermality, mean temperature of the coldest quarter, precipitation of the coldest quarter, and topographic position index had the greater influence on the distribution of *A. spectabilis*. Elevation, mean temperature of the coldest quarter, isothermality, eastness, and precipitation of the warmest quarter had greater influence in distribution of *B. utilis*. The distribution of *P. wallichiana* depended primarily on elevation, isothermality, topographic position index, mean temperature of the coldest quarter, and temperature annual range.

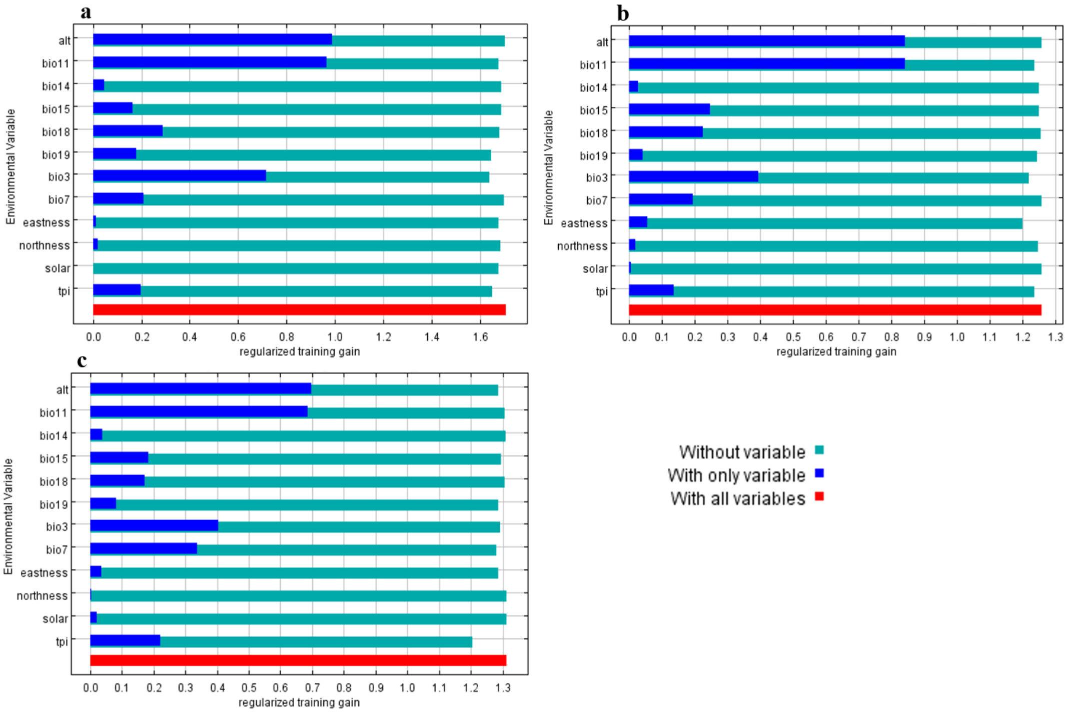


Figure 5-5: Jackknife test of the relative importance of predictor topo-climatic variables for (a) *Abies spectabilis*, (b) *Betula utilis*, and (c) *Pinus wallichiana*. Blue bars indicate the importance of individual variables relative to all topo-climatic variables (red bar).

Table 5-2 Percent contribution of the topo-climatic variables in each species distribution model for the three study species. The variables I examined were isothermality (Bio 3), temperature annual range (Bio7), mean temperature of coldest quarter (Bio11), precipitation of driest month (Bio14), precipitation seasonality (Bio14), precipitation of warmest quarter (Bio18), precipitation of coldest quarter (Bio19), topographic position index (TPI), and solar illumination index (SII).

Abies spectabilis		*Betula utilis*		*Pinus wallichiana*	
Variable	**Percent Contribution**	**Variable**	**Percent Contribution**	**Variable**	**Percent Contribution**
Elevation	39.9	Elevation	38.8	Elevation	39.4
Bio3	28.7	Bio11	24.4	Bio3	21.4
Bio11	11.9	Bio3	20.9	TPI	10.1
Bio19	05.1	Eastness	03.8	Bio11	09.4
TPI	04.3	Bio18	03.3	Bio7	07.8
Bio18	03.2	Bio15	03.2	Bio19	05.2
Bio7	02.1	TPI	02.1	Bio18	02.5
Bio15	01.6	Northness	02.0	Eastness	02.0
Northness	01.0	Bio19	01.0	Bio15	01.6
Eastness	01.0	Bio14	00.4	Northness	00.3
Bio14	00.6	Bio7	00.1	Bio14	00.2
SII	00.6	SII	00.0	SII	00.0

The proportion of suitable habitat for the three study species varied under the alternative climate scenarios (Figure 5-2). The model predicted that suitable habitat area for *A. spectabilis* will increase under all three emissions scenarios in 2050 and 2070. The increase in area is greater in 2070 than in 2050, except under the stable emissions scenario, where a dip in suitable habitat is predicted in 2050 (Table 5-1). The average elevation of *A. spectabilis* was higher under all warming scenarios (Table 5-3, Fig. 5-6a). The model predicted that the suitable habitat area for *B. utilis* will increase in both area (Table 5-1) and elevation (Table 5-3, Figure 5-6b) under all emissions scenarios in 2050 and 2070. The model predicted that the suitable habitat for *P. wallichiana* will not significantly decrease or increase except for stable scenarios in 2070 (Table 5-1). Nevertheless, the average elevation of *P. wallichiana*, was higher in all warming scenarios (Table 5-3, Figure 5-6c).

Table 5-3 Mean average elevation (m) and standard deviation of the current suitable habitat and the future suitable habitat of the three treeline species under the three future climate change scenarios. I compared all future elevation estimates to current using an independent sample t-test. All comparisons were significant ($p < 0.001$).

a. *Abies spectabilis*

Emissions	Current	2050	2070
	3367±721		
Lowest		3488±673	3642±810
Stable		3544±591	3783±791
Highest		4032±802	4212±993

b. *Betula utilis*

Emissions	Current	2050	2070
	3477±633		
Lowest		3971±733	3782±671
Stable		4121±978	4105±1034
Highest		4155±674	4311±857

c. *Pinus wallichiana*

Emissions	Current	2050	2070
	2907±748		
Lowest		3025±806	2968±770
Stable		3009±808	3120±743
Highest		3002±858	3253±842

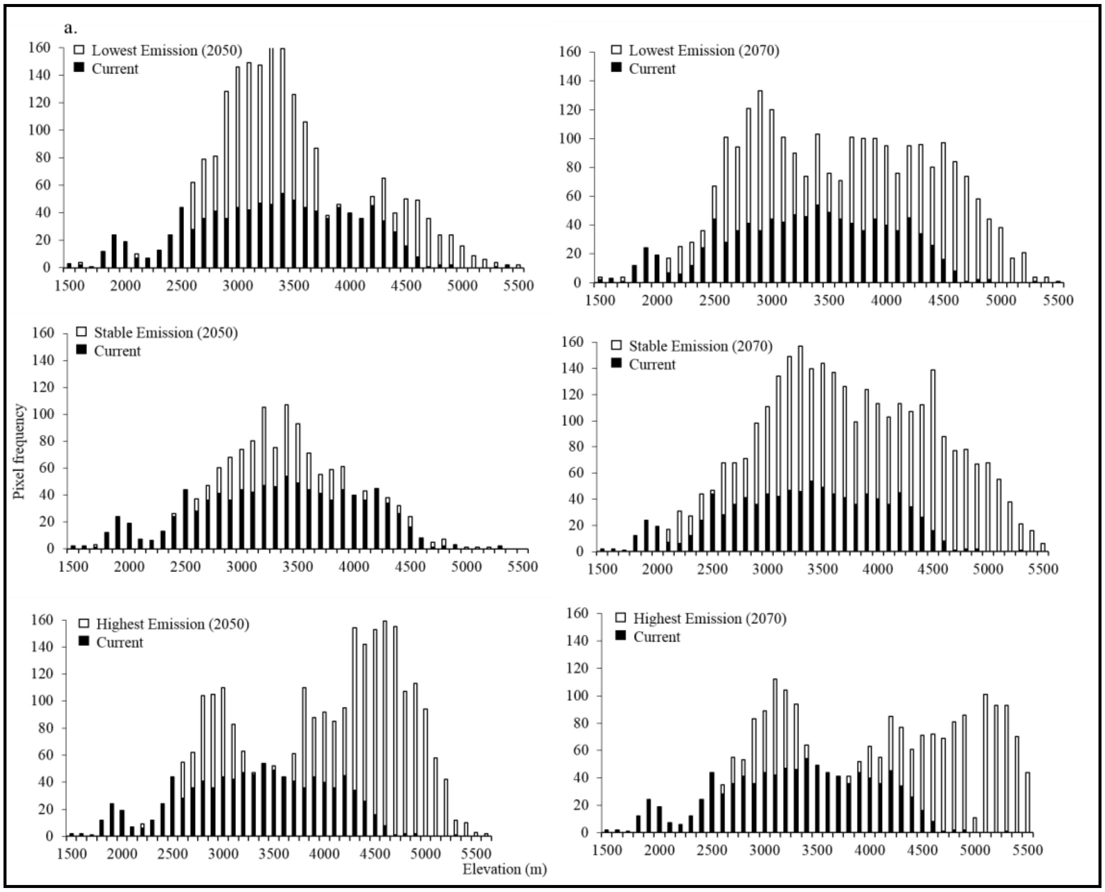


Figure 5-6a: Change in average elevation of suitable habitat for the three study species (a. *Abies spectabilis*) under future climate change scenarios (lowest, stable, and highest).

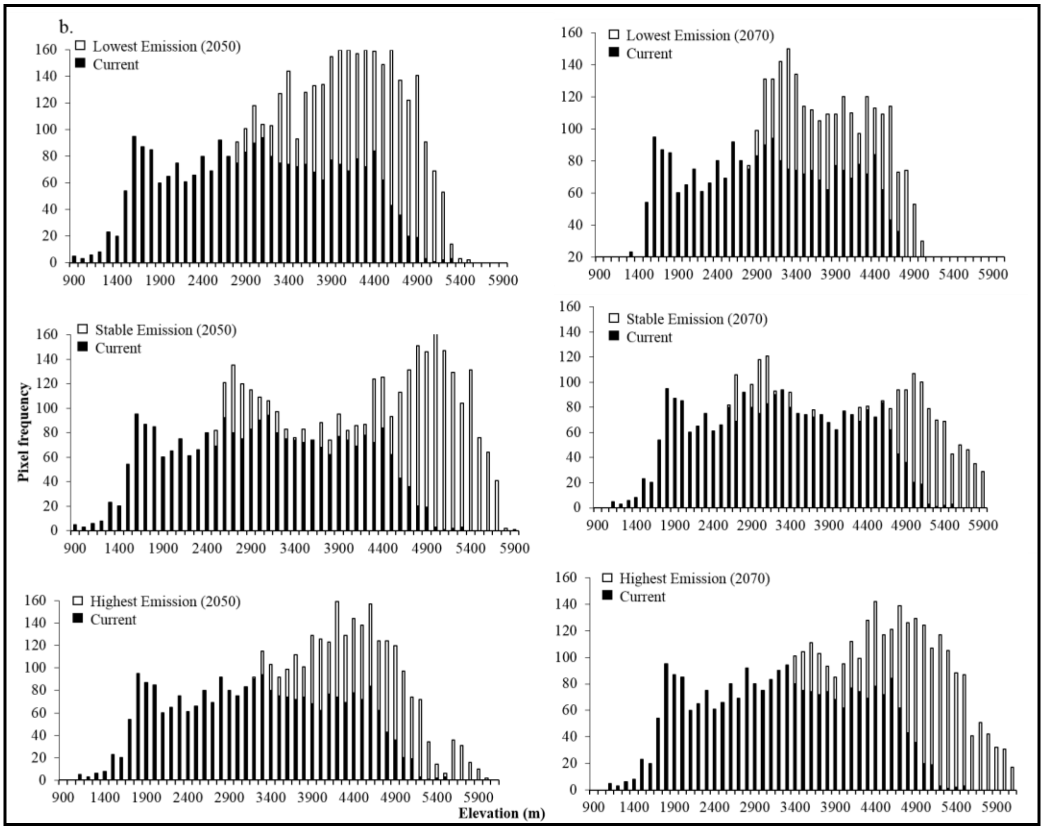


Figure 5-6b: Change in average elevation of suitable habitat for the three study species (b. *Betula utilis*) under future climate change scenarios (lowest, stable, and highest).

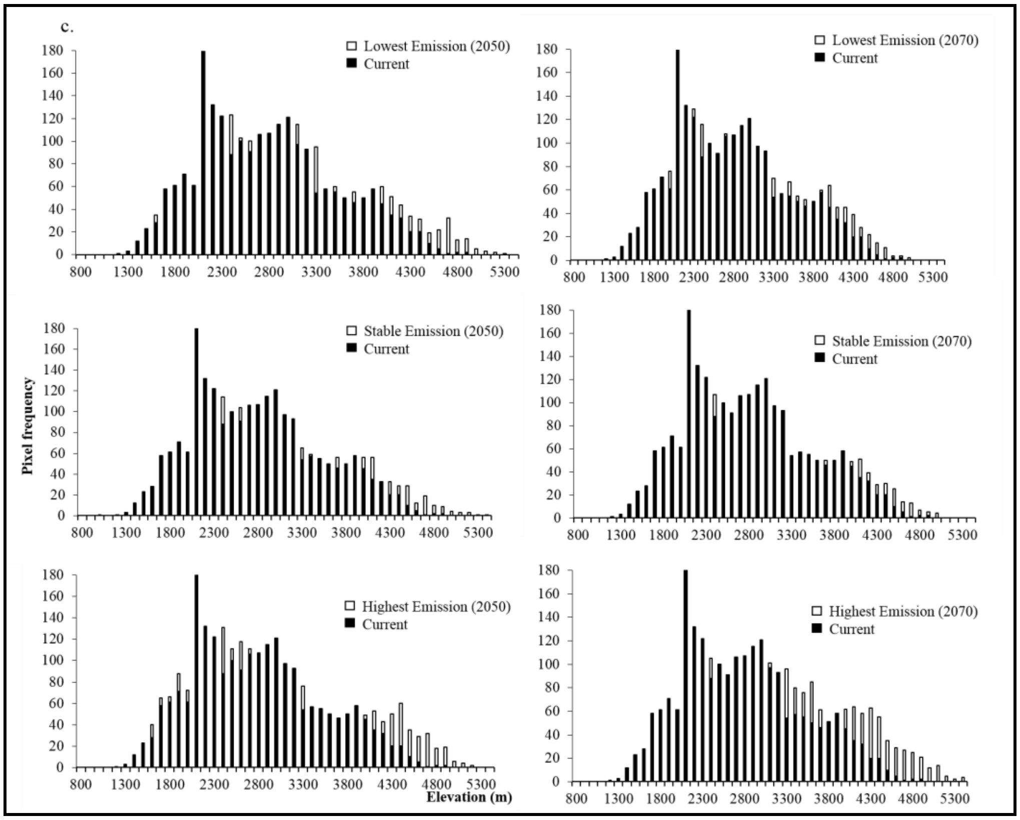


Figure 5-6c: Change in average elevation of suitable habitat for the three study species (c. *Pinus wallichiana*) under future climate change scenarios (lowest, stable, and highest).

DISCUSSION

The distribution of suitable habitat for treeline species in the Nepalese Himalayan Mountains is likely to shift in response to climate change. The species distribution of the three study species examined here were mostly explained by climatic variables, indicating climatic shifts will likely influence future habitat suitability. Explicit analysis confirmed this conclusion. My simulations indicated the habitat suitability of three treeline species will shift toward higher elevation under future predicted climate, with the possibility of undergoing an overall range expansion under alternative future climate models. These predicted shifts have serious consequences for both forest and tundra species in this area.

The contemporary SDMs performed well in describing current patterns when examined through observational and statistical analysis. All model AUC values are close to 0.90, which is considered a moderately-good fit (Kramer-Schadt et al., 2013), and comparable to values obtained in similar studies within this region (*Rhododendron spp.* AUC = 0.78 (Kumar, 2012), *B. utilis* AUC = 0.92 (Schickhoff et al., 2015)). My model results matched the actual existing range of these species based on the authors' local field-based knowledge, existing land cover maps, and ecological maps of Nepal. In Eastern Nepal, the distribution of suitable habitat for *A. spectabilis* indicated dominance in three conservation areas (Kanchenjunga Conservation Area, Makalu Barun National Park, and Sagarmatha National Park) where the species is in fact the dominant forest cover species. Similarly, *B. utilis* is the dominant species in Langtang National Park and Annapurna Conservation Area where the model predicted most of the suitable habitat to be distributed. The model predicted the current distribution of suitable habitat of *P. wallichiana* to be concentrated in the drier areas of Central and Western Nepal, in areas like Rara National Park and Annapurna Conservation Area where the species is dominant.

The primary topo-climatic variables describing the contemporary models for my three study species were insightful given existing knowledge of the ecology of treeline species. Elevation is the most important predictive variable in the model for all three of my species. Elevation may not be directly associated with plant physiology, however it plays an important role in controlling atmospheric pressure, solar radiation, precipitation, and cloud cover (Oke and Thompson, 2015). Thus, elevation is a strong indicator of climatic variables that influence physiology. Mean temperature of coldest quarter is one of the most important climatic variables explaining the contemporary distribution models for all three study species. This finding is consistent with ecological studies that have found the upper altitudinal distribution limit of many treeline species is often determined by low temperature conditions (Körner, 2012). Additionally, mean temperature of coldest quarter and isothermality are related to growing season length, which is a secondary factor that has been identified to limit treeline distribution (Körner, 2012). We should remain conservative in over interpreting these findings as I removed variables that were highly correlated with those included in my model, and simple spatial autocorrelation is an inherent effect in any climatic study (Kumar, 2012). Nevertheless, the strong climatic associations I observed do suggest, in the absence of other limitation, ongoing climate change will influence the distribution of these treeline species.

Although the shift in suitable habitat distribution varied under the alternative future climatic scenarios, there is a high likelihood of treeline advance in the future for the three study species. In terms of change in the area of suitable habitat, my models predicted minimal levels of expansion for *A. spectabilis* and *P. wallichiana* relative to *B. utilis*, which will double or triple under stable and highest emissions scenarios. This is likely due to differences in species-specific requirements that define their distributions. *Pinus wallichiana* prefers dry valleys and foothills and is an early successional species (Ghimire et al., 2011). In contrast, both *A. spectabilis* and *B. utilis* grow on moist north-facing slopes (Ghimire and Lekhak, 2007). *Abies spectabilis* has a broader distribution than *B. utilis*, often occurring on south-facing slopes. *Betula utilis* is often found in areas that receive snowmelt water from mountain peaks above treeline (Shrestha et al., 2007). Future distribution range will depend on how these species specific microsites will change. General Circulation Models (GCMs) project warmer days and nights in the future, which will result in more snow melt that benefits *B. utilis* more than *A. spectabilis* and *P. wallichiana*. Western Nepal is drier than eastern Nepal and monsoon precipitation is projected to increase in Western Nepal which will make western parts more suitable for tree establishment. My model indicated that *B. utilis* will occupy most of the future Western Nepal in both stable and highest emissions scenarios. Nevertheless, I saw average treeline extent advancing under all future climatic scenarios. Many climate models (including CIMIP 5: Shea et al., 2015; LARS-WG: Agarwal et al., 2015; PRECIS HadCM3 and RegCM3 ECHAM5: NCVST, 2009) project an increase in Himalayan winter temperature, which will prolong the growing season making the area above the treeline more favorable for treeline species. These results are similar to previous studies examining species in this area. Schickhoff et al. (2015) predicted *B. utilis* habitat will shift northward throughout all of the Himalayas under future climate change scenarios. Zomer et al. (2014) indicated that sub-alpine conifer forest zones will shift upward by over 400 m between 2000 and 2050. On the other hand, Kumar (2012) predicted that the habitat of *Rhododendron spp*. will shrink under future climate change scenarios in the Sikkim region of the Indian Himalayas, so not all species will necessarily follow this same path.

Potential shifting habitat of these plants might have huge implications for many species in this area that have dependent associations for survival. For instance, habitat of treeline species such as *A. spectabilis* make up the suitable habitat of endangered species, such as the red panda (*Ailurus fulgens*) which prefer to spend most of its time in the branches and on the trunk of A. spectabilis trees (Panthi et al., 2012). Similarly the endangered Himalayan musk deer (*Moschus chrysogaster*) prefer moderate to steep sloped closed canopy of *A. spectabilis* and *B. utilis* sub-alpine forest (Subedi et al., 2012). These species are losing their habitat because *A. spectabilis* and *B. utilis* are under human pressure for timber and fuel wood (Jnawali et al., 2011). Therefore information generated from modeling approaches similar to this study can be utilized for conservation planning and management of endangered species, predicting areas that may be negatively affected by contracting habitat or those that will be opening up for potential expansion.

These results should be couched within the limitations of using a topo-climatic approach for predicting future distributions (Macias-Fauria and Johnson, 2013; Zong et al., 2014). Limitations not included in this analysis may prevent these species from occupying the entirety of their fundamental niche in the future. This could include dispersal limitations of each species (Boisvert-Marsh et al., 2014), which may limit a species ability to establish in newly available suitable habitat. In addition, my projections do not factor in human disturbance (timber and fuel wood harvesting), herbivory (cf. Cairns and Moen, 2004), plant physiology, soil type, snow cover, or land cover. Human disturbance and topographical factors can limit upslope treeline advance (Leonelli et al., 2009). Shrestha and Bawa (2014) emphasized the need for high resolution environmental data that captures microclimates, edaphic conditions, vegetation dynamics, and landscape heterogeneity in SDMs. Kollas et al. (2014) also emphasized the use of high spatial resolution temperature data for predictive modeling of temperature-based niche envelopes recommending the use of topo-climatic variables with a resolution of less than 100 m. They also suggested the use of absolute minimum temperatures in modeling instead of long term means because minimum temperatures determine the phenology of tree species at the cold limit. Building on higher resolution datasets in future studies will improve the accuracy of these results. High resolution climate data is not available for Nepal. Nevertheless this study provides a null model of expectations using the best available data, isolating climatic influences outside of other ecological limitations, providing essential information for future management.

CONCLUSIONS

The model produced a good fit of contemporary species distributions, identifying suitable habitat of the three dominant treeline forming species of the Nepalese Himalayas under present and potential future climates. This approach would be useful for application on other treeline species from the region. Results indicate that the treeline ecotone is likely to transition throughout this region and will likely have significant impacts on the associated plant and animal species. Models predicted that the area above the existing treeline will become suitable for tree establishment. Nevertheless, this establishment will be controlled by factors like natural or human disturbances and ecological interactions with the surrounding shrub communities. Future work examining disturbance factors, species interaction, and inclusion of high resolution satellite imagery and a digital elevation model will improve the accuracy of this work. In addition, for those species expanding, the pattern of migration along the expanding front could significantly influence the amount of genetic variation and chance for local adaptation in this ever changing environment. Future studies examining these effects using emerging landscape genetic tools (Johnson et al., 2016) will be especially informative for future planning.

CHAPTER VI

CONCLUSIONS

Geographic Information Science analysis combined with high-resolution RS imagery can be used for mapping the treeline ecotone, quantifying treeline advancement rate, and monitoring treeline change. The use of RS and GIS in treeline studies is increasing rapidly as these resources become more widespread and their advantages become well-known. Notably, RS and GIS techniques increase the scale at which treeline studies can be performed, ranging from low-resolution, regional-level to high-resolution, patch-level research. In closing, there is no doubt that RS and GIS will greatly advance ecological research, especially given the rapid improvements to such technologies and the increasing availability of high-resolution satellite images.

Remote sensing and GIS based regional scale study indicated that *Abies spectabilis*, *Betula utilis* and *Pinus wallichiana* are the main treeline forming species of the Nepal Himalaya. *Abies spectabilis* and *B. utilis* are dominant in the treeline ecotone of Barun and Manang Valley, respectively. Slope aspect is not important in determining treeline position at the regional scale. However, at the landscape scale, slope aspect affected treeline elevation, particularly at undisturbed locations. This indicated that factors controlling the treeline structure are strongly scale dependent. Treeline type delineation dominate Barun and Manang Valley, respectively, suggesting that topographic and anthropogenic variables are the most important factors in structuring the treeline ecotone. Information on treeline type obtained from this landscape scale study will help predict the responses of forestlines and treelines to temperature changes. Future studies should investigate geomorphological and land use pattern near treeline, and treeline ecotone processes at local scale in order to understand treeline responses to environmental change in the Nepal Himalaya.

Dendroecological based local scale study in DHR, Western Nepal indicated that *Betula utilis* forms the abrupt treeline in, and very few individuals are present above the forestline. In spite of the increasing temperature trend, low regeneration at the treeline ecotone suggests that site-specific biotic and abiotic factors are controlling the treeline dynamics. Seedling establishment above the forestline is limited by a lack of moisture, absence of suitable microsites, and presence of herbivores. To properly investigate the effect of herbivores at the treeline, enclosure experiments are needed. Similarly, the open sky exposure effect can by studied by creating artificial disturbances or canopy cover above the treeline or by transplantation in a controlled area. Local scale study hinted treeline stability, and how this treeline will response in future climate change scenario can be studied through species distribution modeling approach.

The Maxent model produced a good fit of contemporary species distributions, and identified suitable habitat of the three dominant treeline forming species (*Abies spectabilis*, *Betula utilis* and *Pinus wallichiana*) of the Nepalese Himalayas under present and potential future climates. This approach would be useful for application on other treeline species from the region. The results indicate that the treeline ecotone is likely to transition throughout this region and will likely have significant impacts on the associated plant and animal species. Models predicted that the area above the existing treeline will become suitable for tree establishment. Nevertheless, this establishment will be controlled by factors like natural or human disturbances and ecological interactions with the surrounding shrub communities. Future work examining disturbance factors, species interaction, and inclusion of high resolution satellite imagery and a digital elevation model will improve the accuracy of this work. In addition, for those species expanding, the pattern of migration along the expanding front could significantly influence the amount of genetic variation and chance for local adaptation in this ever changing environment. Future studies examining these effects using emerging landscape genetic tools (Johnson et al., 2016) will be especially informative for future planning.

REFERENCES

Agarwal A, Babel MS, and Maskey S (2014) Analysis of future precipitation in the Koshi river basin, Nepal. *Journal of Hydrology* 513: 422-434.

Alatalo JM and Ferrarini A (2017) Braking effect of climate and topography on global change-induced upslope forest expansion. *International Journal of Biometeorology* 61: 541-548.

Allen TR and Walsh SJ (1996) Spatial and compositional pattern of alpine treeline, Glacier National Park, Montana. *Photogrammetric Engineering and Remote Sensing* 62: 1261-1268.

Ameztegui A, Coll L, Brotons L, et al. (2016) Land use legacies rather than climate change are driving the recent upward shift of the mountain tree line in the Pyrenees. *Global Ecology and Biogeography* 25: 263-273.

Bader MY and Ruijten JJ (2008) A topography-based model of forest cover at the alpine tree line in the tropical Andes. *Journal of Biogeography* 35: 711-723.

Baker BB and Moseley RP (2007) Advancing treeline and retreating glaciers: implications for conservation in Yunnan, PR China. *Arctic, Antarctic, and Alpine Research* 39: 200-209.

Baker WL and Weisberg PJ (1995) Landscape analysis of the forest-tundra ecotone in Rocky Mountain National Park, Colorado. *The Professional Geographer* 47: 361-375.

Baker WL and Weisberg PJ (1997) Using GIS to model tree population parameters in the Rocky Mountain National Park forest–tundra ecotone. *Journal of Biogeography* 24: 513-526.

Baker WL, Honaker JJ, and Weisberg PJ (1995) Using aerial photography and GIS to map the forest-tundra ecotone in Rocky Mountain National Park, Colorado, for global change research. *Photogrammetric Engineering and Remote Sensing* 61: 313-320.

Baldwin RA (2009) Use of maximum entropy modeling in wildlife research. *Entropy* 11: 854-866

Batllori E, Camarero JJ, Ninot JM, et al. (2009) Seedling recruitment, survival and facilitation in alpine *Pinus uncinata* tree line ecotones. Implications and potential responses to climate warming. *Global Ecology and Biogeography* 18: 460-472.

Beckage B, Osborne B, Gavin DG, et al. (2008) A rapid upward shift of a forest ecotone during 40 years of warming in the Green Mountains of Vermont. *Proceedings of the National Academy of Sciences* 105: 4197-4202.

Bharti RR, Adhikari SB, and Rawat GS (2012) Accessing vegetation changes in timberline ecotone of Nanda Devi National Park, Uttarakhand. *International Journal of Applied Earth Observation and Geoinformation* 18: 472-479.

Bishop MP, Shroder JF, and Colby JD (2003) Remote sensing and geomorphometry for studying relief production in high mountains. *Geomorphology* 55: 345-361.

Boisvert-Marsh L, Périé C, and de Blois S (2014) Shifting with climate? Evidence for recent changes in tree species distribution at high latitudes. *Ecosphere* 5: 1-33.

Bräuning A (2004) Tree-ring studies in the Dolpo-Himalya (western Nepal). *Tree Rings in Archaeology, Climatology and Ecology* 2: 8-12.

Braunisch V, Patthey P, and Arlettaz R (2016) Where to combat shrub encroachment in alpine timberline ecosystems: combining remotely-sensed vegetation information with species habitat modelling. *PloS One* 11: e0164318.

Brown DG (1994a) Predicting vegetation types at treeline using topography and biophysical disturbance variables. *Journal of Vegetation Science* 5: 641-656.

Brown DG (1994b) Comparison of vegetation-topography relationships at the alpine treeline ecotone. *Physical Geography* 15: 125-145.

Bryant E, Ricketts T, and Richard W (1991) Use of digital elevation data Landsat TM and vector map data to model treeline in the northeastern U.S. *Proceedings of the Eight Thematic Conference on Geologic Remote Sensing* II: 1111-1121.

Bunn AG (2008) A dendrochronology program library in R (dplR). *Dendrochronologia* 26: 115-124.

Butler DR, Malanson GP, Bekker MF, et al. (2003) Lithologic, structural, and geomorphic controls on ribbon forest patterns in a glaciated mountain environment. *Geomorphology* 55: 203-217.

Butler DR, Malanson GP, Walsh SJ, et al. (2007) Influences of geomorphology and geology on alpine treeline in the American West—More important than climatic influences?. *Physical Geography* 28: 434-450.

Cairns DM (2001) A comparison of methods for predicting vegetation type. *Plant Ecology* 156: 3-18.

Cairns DM and Moen J (2004) Herbivory influences tree lines. *Journal of Ecology* 92: 1019-1024.

Cairns DM, Lafon C, Moen J, et al. (2007) Influences of animal activity on treeline position and pattern: implications for treeline responses to climate change. *Physical Geography* 28: 419-433.

Camarero JJ and Gutiérrez E (2004) Pace and pattern of recent treeline dynamics: response of ecotones to climatic variability in the Spanish Pyrenees. *Climatic Change* 63: 181-200.

Carlson BZ, Randin CF, Boulangeat I, et al. (2013) Working toward integrated models of alpine plant distribution. *Alpine Botany* 123: 41-53.

Carpenter C and Zomer R (1996) Forest ecology of the Makalu-Barun National Park and Conservation Area, Nepal. *Mountain Research and Development* 16: 135-148.

Case BS and Buckley HL (2015) Local-scale topoclimate effects on treeline elevations: a country-wide investigation of New Zealand's southern beech treelines. *PeerJ* 3: e1334.

Chaudhary RP (1998) *Biodiversity in Nepal: status and conservation*. Bangkok, Thailand: Tecpress Books.

Chen L, Mi X, Comita LS, et al. (2010) Community-level consequences of density dependence and habitat association in a subtropical broad-leaved forest. *Ecology Letters* 13: 695-704.

Chhetri PK (2017) Predicting upslope expansion of sub-alpine forest in the Makalu Barun National Park, eastern Nepal, with a hybrid cartographic model. *Journal of Forestry Research*. DOI: 10.1007/s11676-017-0421-8

Chhetri PK and Cairns DM (2015) Contemporary and historic population structure of *Abies spectabilis* at treeline in Barun valley, eastern Nepal Himalaya. *Journal of Mountain Science* 15: 558-570.

Chhetri PK and Cairns DM (2016) Dendroclimatic response of *Abies spectabilis* at treeline ecotone of Barun Valley, eastern Nepal Himalaya. *Journal of Forestry Research* 27: 1163-1170.

Chhetri PK and Shrestha KB (2009) Dendrochronology and climate change study in Nepal: a preview. *Banko Janakari* 19: 42-43.

Chhetri PK, Bista R, and Cairns DM (2016) Population structure and dynamics of *Abies spectabilis* at treeline ecotone of Barun Valley, Makalu Barun National Park, Nepal. *Acta Ecologica Sinica* 36: 269-274.

Chhetri PK, Shrestha K, and Cairns DM (2017) Topography and human disturbances are major controlling factor in treeline pattern at Barun and Manang area in the Nepal Himalaya. *Journal of Mountain Science* 14: 119-127

Cullen LE, Palmer JG, Duncan RP, et al. (2001) Climate change and tree-ring relationships of *Nothofagus menziesii* tree-line forests. *Canadian Journal of Forest Research* 31: 1981-1991.

Danby RK and Hik DS (2007) Variability, contingency and rapid change in recent subarctic alpine tree line dynamics. *Journal of Ecology* 95: 352-363.

Danzeglocke J. (2005) Remote sensing of upper timberline elevation in the Alps on different scales. *New strategies for European remote sensing. Proceedings of the 24th Symposium of the European Association of Remote Sensing Laboratories, Dubrovnik, Croatia, 25-27 May 2004.*: Millpress Science Publishers, 145-151.

Devi N, Hagedorn F, Moiseev P, et al. (2008) Expanding forests and changing growth forms of Siberian larch at the Polar Urals treeline during the 20th century. *Global Change Biology* 14: 1581-1591.

Dolanc CR, Thorne JH, and Safford HD (2013) Widespread shifts in the demographic structure of subalpine forests in the Sierra Nevada, California, 1934 to 2007. *Global Ecology and Biogeography* 22: 264-276.

Dubey B, Yadav YR, Sing J, et al. (2003) Upward shift of Himalayan pine in Western Himalaya, India. *Current Science* 85: 1135-1136.

Elith J and Graham CH (2009) Do they? How do they? Why do they differ? On finding reasons for differing performances of species distribution models. *Ecography* 32: 66-77.

Elith J, Phillips SJ, Hastie T, et al. (2011) A statistical explanation of MaxEnt for ecologists. *Diversity and Distributions* 17: 43-57.

Elliott GP (2011) Influences of 20th-century warming at the upper tree line contingent on local-scale interactions: evidence from a latitudinal gradient in the Rocky Mountains, USA. *Global Ecology and Biogeography* 20: 46-57.

Elliott GP (2012) Extrinsic regime shifts drive abrupt changes in regeneration dynamics at upper treeline in the Rocky Mountains, USA. *Ecology* 93: 1614-1625.

Fagan WF, Fortin MJ, and Soykan C (2003) Integrating edge detection and dynamic modeling in quantitative analyses of ecological boundaries. *BioScience* 53: 730-738.

Fielding AH and Bell JF (1997) A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environmental Conservation* 24: 38-49.

Fissore V, Motta R, Palik B, et al. (2015) The role of spatial data and geomatic approaches in treeline mapping: a review of methods and limitations. *European Journal of Remote Sensing* 48: 777-792.

Flora of Nepal (2014) Royal Botanic Gardens Edinburgh. http://padme.rbge.org.uk/floraofnepal/index.php?page=home. Accessed on 18 November 2014.

Forrest JL, Wikramanayake E, Shrestha R, et al. (2012) Conservation and climate change: Assessing the vulnerability of snow leopard habitat to treeline shift in the Himalaya. *Biological Conservation* 150: 129-135.

Franklin J (2010) Moving beyond static species distribution models in support of conservation biogeography. *Diversity and Distributions* 16: 321-330.

Fritts HC (1976) *Tree rings and climate*. San Diego, California: Academic.

Gaire NP, Bhuju DR, Koirala M, et al. (2017) Tree-ring based spring precipitation reconstruction in western Nepal Himalaya since AD 1840. *Dendrochronologia* 42: 21-30.

Gaire NP, Koirala M, Bhuju DR, et al. (2014) Treeline dynamics with climate change at the central Nepal Himalaya. *Climate of the Past* 10: 1277-1290.

Gaire NP, Koirala M, Bhuju DR, et al. (2016) Site-and species-specific treeline responses to climatic variability in eastern Nepal Himalaya. *Dendrochronologia* 41: 44-56.

Gallardo B, Zieritz A, and Aldridge DC (2015) The importance of the human footprint in shaping the global distribution of terrestrial, freshwater and marine invaders. *PLoS One* 10: e0125801.

Gao Y and Zhang W (2009) A simple empirical topographic correction method for ETM+ imagery. *International Journal of Remote Sensing* 30: 2259-2275.

Gartzia M, Alados CL, and Pérez-Cabello F (2014) Assessment of the effects of biophysical and anthropogenic factors on woody plant encroachment in dense and sparse mountain grasslands based on remote sensing data. *Progress in Physical Geography* 38: 201-217.

GBIF (2014) Global Biodiversity Information Facility. http://www.gbif.org/resources/2970 (Accessed 15 December 2014)

Gehrig-Fasel J, Guisan A, and Zimmermann NE (2007) Tree line shifts in the Swiss Alps: Climate change or land abandonment? *Journal of Vegetation Science* 18: 571-582.

Germino MJ and Smith WK (2000) High resistance to low temperature photoinhibition in two alpine, snowbank species. *Physiologia Plantarum* 110: 89-95.

Germino MJ, Smith WK, and Resor AC (2002) Conifer seedling distribution and survival in an alpine-treeline ecotone. *Plant Ecology* 162: 157-168.

Ghimire B, Mainali KP, Lekhak HD, et al. (2011) Regeneration of *Pinus wallichiana* AB Jackson in a trans-Himalayan dry valley of north-central Nepal. *Himalayan Journal of Sciences* 6: 19-26.

Ghimire BK and Lekhak HD (2007) Regeneration of *Abies spectabilis* (D. Don) Mirb. in subalpine forest of Upper Manang, North central Nepal. In Chaudhary RP, Aase T H, Veetas OR, and Subedi BP (eds) *Local Effects of Global Changes in the Himalayas: Manang, Nepal*. Tribhuvan University, Nepal and University of Bergen, Norway, 139-149.

Grace J, Berninger F, and Nagy L (2002) Impacts of climate change on the tree line. *Annals of Botany* 90: 537-544.

Greenwood S and Jump AS (2014) Consequences of treeline shifts for the diversity and function of high altitude ecosystems. *Arctic, Antarctic, and Alpine Research* 46: 829-840.

Greenwood S, Chen JC, Chen CT, et al. (2015) Temperature and sheltering determine patterns of seedling establishment in an advancing subtropical treeline. *Journal of Vegetation Science* 26: 711-721.

Groen TA, Fanta HG, Hinkov G, et al. (2012) Tree line change detection using historical hexagon mapping camera imagery and Google earth data. *GIScience & Remote Sensing* 49: 933-943.

Gu D and Gillespie A (1998) Topographic normalization of Landsat TM images of forest based on subpixel sun–canopy–sensor geometry. *Remote Sensing of Environment* 64: 166-175.

Guo D, Zhang H, Hou G, et al. (2014) Topographic controls on alpine treeline patterns on Changbai Mountain, China. *Journal of Mountain Science* 11: 429-441.

Harsch MA and Bader MY (2011) Treeline form–a potential key to understanding treeline dynamics. *Global Ecology and Biogeography* 20: 582-596.

Harsch MA, Hulme PE, McGlone MS, et al. (2009) Are treelines advancing? A global meta-analysis of treeline response to climate warming. *Ecology Letters* 12: 1040-1049.

Hernandez PA, Franke I, Herzog SK, et al. (2008) Predicting species distributions in poorly-studied landscapes. *Biodiversity and Conservation* 17: 1353-1366.

Hijmans RJ and Graham CH (2006) The ability of climate envelope models to predict the effect of climate change on species distributions. *Global Change Biology* 12: 2272-2281.

Hijmans RJ, Cameron SE, Parra JL, et al. (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25: 1965-1978.

Holdridge LR (1947) Determination of world plant formations from simple climatic data. *Science* 105: 367-368.

Holtmeier FK (2009) *Mountain timberlines: ecology, patchiness, and dynamics*. Dordrecht, Netherlands: Kluwer Academic Publishers.

Holtmeier FK and Broll G (2005) Sensitivity and response of northern hemisphere altitudinal and polar treelines to environmental change at landscape and local scales. *Global Ecology and Biogeography* 14: 395-410.

Holtmeier FK and Broll G (2012) Landform influences on treeline patchiness and dynamics in a changing climate. *Physical Geography* 33: 403-437.

Hughes NM, Johnson DM, Akhalkatsi M, et al. (2009). Characterizing *Betula litwinowii* seedling microsites at the alpine-treeline ecotone, Central Greater Caucasus Mountains, Georgia. *Arctic, Antarctic, and Alpine Research* 41: 112-118.

Irl SD, Anthelme F, Harter DE, et al. (2015) Patterns of island treeline elevation–a global perspective. *Ecography* 39: 427-436.

Jacob M, Frankl A, Hurni H, et al. (2017) Land cover dynamics in the Simien Mountains (Ethiopia), half a century after establishment of the National Park. *Regional Environmental Change* 17: 777-787.

Jnawali SR, Baral HS, Lee S, et al. (compilers) (2011). The status of Nepal mammals: The national red list series, Department of National Parks and Wildlife Conservation Kathmandu, Nepal.

Jobbagy EG and Jackson RB (2000) Global controls of forest line elevation in the northern and southern hemispheres. *Global Ecology and Biogeography* 9: 253-268.

Johnson JS, Gaddis KD, Cairns DM, et al. (2016) Plant responses to global change: Next generation biogeography. *Physical Geography* 37: 93-119.

Karki JB and Thapa BB (2007) A report on status of blue sheep and Himalayan thar in Dhorpatan Hunting Reserve. Report submitted to DNPWC, Kathmandu.

Kimball KD and Weihrauch DM (2000) Alpine vegetation communities and the alpine-treeline ecotone boundary in New England as biomonitors for climate change. *RMRS-P-15* 3: 93-101.

Klasner FL and Fagre DB (2002) A half century of change in alpine treeline patterns at Glacier National Park, Montana, USA. *Arctic, Antarctic, and Alpine Research* 34: 49-56.

Klinge M, Böhner J, and Erasmi S (2014) Modelling forest lines and forest distribution patterns with remote sensing data in a mountainous region of semi-arid Central Asia. *Biogeosciences Discussions* 11: 14667-14698.

Kollas C, Körner C, and Randin CF (2014) Spring frost and growing season length co-control the cold range limits of broad leaved trees. *Journal of Biogeography* 41: 773-783.

Körner C (2012) *Alpine treelines: functional ecology of the global high elevation tree limits*. Basel, Switzerland: Springer.

Körner C. and Paulsen J (2004) A world-wide study of high altitude treeline temperatures. *Journal of Biogeography* 31: 713-732.

Kramer-Schadt S, Niedballa J, Pilgrim JD, et al. (2013) The importance of correcting for sampling bias in MaxEnt species distribution models. *Diversity and Distributions* 19: 1366-1379.

Kullman L (2007) Tree line population monitoring of *Pinus sylvestris* in the Swedish Scandes, 1973–2005: implications for tree line theory and climate change ecology. *Journal of Ecology* 95: 41-52.

Kumar P (2012) Assessment of impact of climate change on Rhododendrons in Sikkim Himalayas using Maxent modelling: limitations and challenges. *Biodiversity and Conservation* 21: 1251-1266.

Kumar S and Stohlgren TJ (2009) Maxent modeling for predicting suitable habitat for threatened and endangered tree *Canacomyrica monticola* in New Caledonia. *Journal of Ecology and the Natural Environment* 1: 94-98.

Leonelli G, Masseroli A, and Pelfini M (2016) The influence of topographic variables on treeline trees under different environmental conditions. *Physical Geography* 37: 56-72.

Leonelli G, Pelfini M, and di Cella UM (2009) Detecting climatic treelines in the Italian Alps: the influence of geomorphological factors and human impacts. *Physical Geography* 30: 338-352.

Leonelli G, Pelfini M, di Cella UM, et al. (2011) Climate warming and the recent treeline shift in the European Alps: the role of geomorphological factors in high-altitude sites. *Ambio* 40: 264-273.

Liang E, Dawadi B, Pederson N, et al. (2014) Is the growth of birch at the upper timberline in the Himalayas limited by moisture or by temperature?. *Ecology* 95: 2453-2465.

Liang E, Wang Y, Eckstein D, et al. (2011) Little change in the fir tree-line position on the southeastern Tibetan Plateau after 200 years of warming. *New Phytologist* 190: 760-769.

Lin Y, Ren JY, and Yue M (2009) Spatial patterns and associations in a birch-fir forest in Mt. Taibai. *Journal of Wuhan Botanical Research* 27: 47-54. [In Chinese].

Lingua E, Cherubini P, Motta R, et al. (2008) Spatial structure along an altitudinal gradient in the Italian central Alps suggests competition and facilitation among coniferous species. *Journal of Vegetation Science* 19: 425-436.

López-Serrano PM, Corral-Rivas JJ, Díaz-Varela RA, et al. (2016) Evaluation of radiometric and atmospheric correction algorithms for aboveground forest biomass estimation using Landsat 5 TM data. *Remote Sensing* 8: 369.

Lovari S, Ventimiglia M, and Minder I (2013) Food habits of two leopard species, competition, climate change and upper treeline: a way to the decrease of an endangered species?. *Ethology Ecology & Evolution* 25: 305-318.

Luo G and Dai L (2013) Detection of alpine tree line change with high spatial resolution remotely sensed data. *Journal of Applied Remote Sensing* 7: 073520-073520.

MacDonald GM, Szeicz JM, Claricoates J, et al. (1998) Response of the central Canadian treeline to recent climatic changes. *Annals of the Association of American Geographers* 88: 183-208.

Macias-Fauria M and Johnson EA (2013) Warming-induced upslope advance of subalpine forest is severely limited by geomorphic processes. *PNAS* 110: 8117-8122.

Maher EL and Germino MJ (2006) Microsite differentiation among conifer species during seedling establishment at alpine treeline. *Ecoscience* 13, 334-341.

Malanson GP, Resler LM, Bader MY, et al. (2011). Mountain treelines: a roadmap for research orientation. *Arctic, Antarctic, and Alpine Research* 43:167-77.

Manandhar N (2002) *Plants and People of Nepal*. Portland, USA: Timber Press. Inc.

Mathisen IE, Mikheeva A, Tutubalina OV, et al. (2014) Fifty years of tree line change in the Khibiny Mountains, Russia: advantages of combined remote sensing and dendroecological approaches. *Applied Vegetation Science* 17: 6-16.

Mathisen IE, Mikheeva A, Tutubalina, et al. (2014). Fifty years of tree line change in the Khibiny Mountains, Russia: advantages of combined remote sensing and dendroecological approaches. *Applied Vegetation Science* 17: 6-16.

Merow C, Smith MJ, and Silander JA (2013) A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter. *Ecography* 36: 1058-1069.

Miehe G, Miehe S, and Schlütz F (2009) Early human impact in the forest ecotone of southern High Asia (Hindu Kush, Himalaya). *Quaternary Research* 71: 255-265.

Miehe G, Miehe S, Vogel J, et al. (2007) Highest treeline in the northern hemisphere found in southern Tibet. *Mountain Research and Development* 27: 169-173.

Mishra NB and Mainali KP (2017) Greening and browning of the Himalaya: Spatial patterns and the role of climatic change and human drivers. *Science of The Total Environment* 587: 326-339.

Moen J, Aune K, Edenius L, et al. (2004) Potential effects of climate change on treeline position in the Swedish mountains. *Ecology and Society* 9: 16.

Moran MS, Bryant R, Thome K, et al. (2001) A refined empirical line approach for reflectance factor retrieval from Landsat-5 TM and Landsat-7 ETM+. *Remote Sensing of Environment* 78: 71-82.

Müller M, Schickhoff U, Scholten T, et al. (2016) How do soil properties affect alpine treelines? General principles in a global perspective and novel findings from Rolwaling Himal, Nepal. *Progress in Physical Geography* 40: 135-160.

Nagendra H (2001) Using remote sensing to assess biodiversity. *International Journal of Remote Sensing* 22: 2377-2400.

Nepal Climate Vulnerability Study Team (NCVST) (2009) *Vulnerability through the eyes of vulnerable: Climate change induced uncertainties and Nepal's development predicaments*. Boulder, CO and Kathmandu, Nepal: Institute for Social and Environmental Transition (ISET), & Institute for Social and Environmental Transition-Nepal (ISET-N).

Oke OA and Thompson KA (2015) Distribution models for mountain plant species: The value of elevation. *Ecological Modelling* 301: 72-77.

Oke TR (1987) *Boundary layer climates*. New York, USA: Methuen & Co.

Panigrahy S, Anitha D, Kimothi MM, et al. (2010) Timberline change detection using topographic map and satellite imagery. *Tropical Ecology* 51: 87-91.

Panthi S, Aryal A, Raubenheimer D, et al. (2012) Summer diet and distribution of the red panda (*Ailurus fulgens fulgens*) in Dhorpatan Hunting Reserve, Nepal. *Zoological Studies* 51: 701-709.

Paudel S and Vetaas OR (2014) Effects of topography and land use on woody plant species composition and beta diversity in an arid Trans-Himalayan landscape, Nepal. *Journal of Mountain Science* 11: 1112-1122.

Paulsen J and Körner C (2001) GIS-analysis of tree-line elevation in the Swiss Alps suggests no exposure effect. *Journal of Vegetation Science* 12: 817-824.

Paulsen J and Körner C (2014) A climate-based model to predict potential treeline position around the globe. *Alpine Botany* 124: 1-12.

Paulsen J, Weber UM, and Körne C (2000) Tree growth near treeline: abrupt or gradual reduction with altitude?. *Arctic, Antarctic, and Alpine Research* 32: 14-20.

Pearson RG, Raxworthy CJ, Nakamura M, et al. (2007) Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. *Journal of Biogeography* 34: 102-117.

Penuelas J, Ogaya R, Boada M, et al. (2007) Migration, invasion and decline: changes in recruitment and forest structure in a warming-linked shift of European beech forest in Catalonia (NE Spain). *Ecography* 30: 829-837.

Pettorelli N, Laurance WF, O'Brien TG, et al. (2014). Satellite remote sensing for applied ecologists: opportunities and challenges. *Journal of Applied Ecology* 51: 839-848.

Phillips SJ, Anderson RP, and Schapire RE 2006. Maximum entropy modelling of species geographic distributions. *Ecological Modeling* 190: 231-259.

Piermattei A, Renzaglia F, and Urbinati C (2012) Recent expansion of *Pinus nigra* Arn. above the timberline in the central Apennines, Italy. *Annals of Forest Science* 69: 509-517.

Porfirio LL, Harris RM, Lefroy EC, et al. (2014) Improving the use of species distribution models in conservation planning and management under climate change. *PloS One* 9: e113749.

Potter C (2016) Vegetation cover change in Glacier National Park detected using 25 years of Landsat satellite image analysis. *Journal of Biodiversity Management and Forestry*. DOI: 10.4172/2327-4417.1000152

Randin CF, Engler R, Normand S, et al. (2009) Climate change and plant distribution: local models predict high-elevation persistence. *Global Change Biology* 15: 1557-1569.

Ren JY, Kadir A, and Yue M (2015) The role of tree fall gaps in the natural regeneration of birch forests in the Taibai Mountains. *Applied Vegetation Science* 18: 64-74.

Resler LM, Butler DR, and Malanson GP (2005) Topographic shelter and conifer establishment and mortality in an alpine environment, Glacier National Park, Montana. *Physical Geography* 26: 112-125.

Resler LM, Fonstad MA, and Butler DR (2004) Mapping the alpine treeline ecotone with digital aerial photography and textural analysis. *Geocarto International* 19: 37-44.

Richardson AD and Friedland AJ (2009) A review of the theories to explain arctic and alpine treelines around the world. *Journal of Sustainable Forestry* 28: 218-242.

Ripley BD (1977) Modelling spatial patterns. *Journal of the Royal Statistical Society. Series B (Methodological)* 39: 172-212.

Roughgarden J, Running S, and Matson PA (1991) What does remote sensing do for ecology? *Ecology* 72: 1918-1922.

Schickhoff U (2005) The upper timberline in the Himalayas, Hindu Kush and Karakorum: A review of geographical and ecological aspects. In Broll G and Keplin B (eds) *Mountain Ecosystems: Studies in Treeline Ecology*. Berlin, Germany: Springer, 275-354.

Schickhoff U, Bobrowski M, Böhner J, et al. (2015) Do Himalayan treelines respond to recent climate change? An evaluation of sensitivity indicators. *Earth System Dynamic* 6: 245–265.

Schwab N, Schickhoff U, Müller M, et al. (2016) Treeline responsiveness to climate warming: insights from a krummholz treeline in Rolwaling Himal, Nepal. In Singh RB, Schickhoff U, and Mal S (eds) *Climate change, glacier response, and vegetation dynamics in the Himalaya*. Berlin, Germany: Springer, 307-345.

Shea JM, Immerzeel WW, Wagnon P, et al. (2015) Modelling glacier change in the Everest region, Nepal Himalaya. *The Cryosphere* 9: 1105-1128.

Shi P and Wu N (2013) The Timberline ecotone in the Himalayan region: An ecological review. In Wu N, Rawat GS, Joshi S, Ismail M, and Sharma E (eds) *High-altitude rangelands and their interfaces in the Hindu Kush Himalayas*. Kathmandu, Nepal: International Centre for Integrated Mountain Development (ICIMOD), 108-116.

Shrestha AB and Aryal R (2011) Climate change in Nepal and its impact on Himalayan glaciers. *Regional Environmental Change* 11: S65-S77.

Shrestha AB and Devkota LP (2010) Climate change in the eastern Himalayas: observed trends and model projections. International Centre for Integrated Mountain Development (ICIMOD). Kathmandu, Nepal.

Shrestha AB, Wake CP, Dibb JE (2000) Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. *International Journal of Climatology* 20: 317-327.

Shrestha BB, Ghimire B, Lekhak HD, et al. (2007) Regeneration of treeline birch (*Betula utilis* D. Don) forest in a trans-Himalayan dry valley in central Nepal. *Mountain Research and Development* 27: 259-267.

Shrestha KB, Hofgaard A, and Vandvik V (2014) Recent treeline dynamics are similar between dry and mesic areas of Nepal, central Himalaya. *Journal of Plant Ecology* 8: 347-358.

Shrestha UB and Bawa KS (2014) Impact of climate change on potential distribution of Chinese caterpillar fungus (*Ophiocordyceps sinensis*) in Nepal Himalaya. *PloS One 9*: e106405.

Simms ÉL and Ward H (2013) Multisensor NDVI-based monitoring of the tundra-taiga interface (Mealy Mountains, Labrador, Canada). *Remote Sensing* 5: 1066-1090.

Singh CP, Panigrahy S, Parihar JS, et al. (2013) Modeling environmental niche of Himalayan birch and remote sensing based vicarious validation. *Tropical Ecology* 54: 321-329.

Singh CP, Panigrahy S, Thapliyal A, et al. (2012) Monitoring the alpine treeline shift in parts of the Indian Himalayas using remote sensing. *Current Science* 102: 559-562.

Speer JH (2010) *Fundamentals of tree-ring research*. Tucson, USA: University of Arizona Press.

Srur AM, Villalba R, Rodríguez-Catón M, et al. (2016) Establishment of *Nothofagus pumilio* at upper treelines across a precipitation gradient in the northern Patagonian Andes. *Arctic, Antarctic, and Alpine Research* 48: 755-766.

Stainton JDA (1972) *Forests of Nepal*. London, UK: John Murray.

Steyaert LT and Goodchild MF (1994) Integrating geographic information systems and environmental simulation models: a status review. In Michener WK, Brunt JW, and Stafford SG (eds) *Environmental information management and analysis: ecosystem to global scales*. Philadelphia, USA: Taylor&Francis, 333-356.

Stueve KM, Isaacs RE, Tyrrell LE, et al. (2011) Spatial variability of biotic and abiotic tree establishment constraints across a treeline ecotone in the Alaska Range. *Ecology* 92: 496-506.

Subedi A, Aryal A, Koirala RK, et al. (2012) Habitat ecology of Himalayan musk deer (*Moschus chrysogaster*) in Manaslu Conservation Area, Nepal. *International Journal of Zoological Research* 8: 81-89.

Suwal MK, Shrestha KB, Guragain L, et al. (2016) Land-use change under a warming climate facilitated upslope expansion of Himalayan silver fir (*Abies spectabilis* (D. Don) Spach). *Plant Ecology* 1-10. DOI: 10.1007/s11258-016-0624-7

Szerencsits E (2012) Swiss tree lines–a GIS-based approximation. *Landscape Online* 28: 1-18.

Telwala Y, Brook BW, Manish K, et al. (2013) Climate-induced elevational range shifts and increase in plant species richness in a Himalayan biodiversity epicentre. *PLoS One* 8: e57103.

Tiwari A, Fan ZX, Jump AS, et al. (2016) Gradual expansion of moisture sensitive *Abies spectabilis* forest in the Trans-Himalayan zone of central Nepal associated with climate change. *Dendrochronologia* 41: 34-43.

Trant AJ and Hermanutz L (2014) Advancing towards novel tree lines? A multispecies approach to recent tree line dynamics in subarctic alpine Labrador, northern Canada. *Journal of Biogeography* 41: 1115-1125.

Treml V, Šenfeldr M, Chuman T, et al. (2016) Twentieth century treeline ecotone advance in the Sudetes Mountains (Central Europe) was induced by agricultural land abandonment rather than climate change. *Journal of Vegetation Science* 27: 1209-1221.

Troll C (1973) The upper timberlines in different climatic zones. *Arctic and Alpine Research*: A3-A18.

Truong C, Palmé AE, and Felber F (2007) Recent invasion of the mountain birch *Betula pubescens* ssp. tortuosa above the treeline due to climate change: genetic and ecological study in northern Sweden. *Journal of Evolutionary Biology* 20: 369-380.

Tueller PT (1998) Approaches to mapping ecotone boundaries using emerging remote sensing technology. *Proceedings Rocky Mountain Research Stations* 11: 78-83.

Uddin K, Shrestha HL, Murthy M, et al. (2015) Development of 2010 national land cover database for the Nepal. *Journal of Environmental Management* 148: 82-90.

Virtanen T, Mikkola K, Nikula A, et al. (2004) Modeling the location of the forest line in northeast European Russia with remotely sensed vegetation and GIS-based climate and terrain data. *Arctic, Antarctic, and Alpine Research* 36: 314-322.

Vittoz P, Rulence B, Largey T, et al. (2008) Effects of climate and land-use change on the establishment and growth of cembran pine (*Pinus cembra* L.) over the altitudinal treeline ecotone in the Central Swiss Alps. *Arctic, Antarctic, and Alpine Research* 40: 225-232.

Wallentin G, Tappeiner U, Strobl J, et al. (2008) Understanding alpine tree line dynamics: an individual-based model. *Ecological Modelling* 218: 235-246.

Walsh SJ and Kelly NM (1990) Treeline migration and terrain variability: integration of remote sensing digital enhancements and digital elevation models. *Proceedings of Applied Geography Conferences* 24-32.

Walsh SJ, Butler DR, Allen TR, et al. (1994) Influence of snow patterns and snow avalanches on the alpine treeline ecotone. *Journal of Vegetation Science* 5: 657-672.

Walsh SJ, Butler DR, and Malanson GP (1998) An overview of scale, pattern, process relationships in geomorphology: a remote sensing and GIS perspective. *Geomorphology* 21: 183-205.

Walsh SJ, Butler DR, Malanson GP, et al. (2003) Mapping, modeling, and visualization of the influences of geomorphic processes on the alpine treeline ecotone, Glacier National Park, MT, USA. *Geomorphology* 53: 129-145

Wang Q, Zhao C, Gao C, et al. (2017) Effects of environmental variables on seedling-sapling distribution of Qinghai spruce (*Picea crassifolia*) along altitudinal gradients. *Forest Ecology and Management* 384: 54-64.

Wang T, Zhang QB, and Ma K (2006) Treeline dynamics in relation to climatic variability in the central Tianshan Mountains, northwestern China. *Global Ecology and Biogeography* 15: 406-415.

Wang W, Körner C, Zhang Z, et al. (2013): No slope exposure effect on alpine treeline position in the Three Parallel Rivers Region, SW China. *Alpine Botany* 123: 87-95.

Wang Y, Camarero JJ, Luo T, et al. (2012) Spatial patterns of Smith fir alpine treelines on the south-eastern Tibetan Plateau support that contingent local conditions drive recent treeline patterns. *Plant Ecology & Diversity* 5: 311-321.

Weiss DJ and Walsh SJ (2009) Remote sensing of mountain environments. *Geography Compass* 3: 1-21.

White JD, Kroh GC, and Pinder JE (1995) Forest mapping at Lassen Volcanic National Park, California, using Landsat TM data and a geographical information system. *Photogrammetric Engineering and Remote Sensing* 61: 299-305.

Wisz MS, Hijmans RJ, Li J, et al. (2008) Effects of sample size on the performance of species distribution models. *Diversity and Distributions* 14: 763-773.

Wit HA, Bryn A, Hofgaard A, et al. (2014) Climate warming feedback from mountain birch forest expansion: reduced albedo dominates carbon uptake. *Global Change Biology* 20: 2344-2355.

Xu J, Grumbine RE, Shrestha A, et al. (2009) The melting Himalayas: cascading effects of climate change on water, biodiversity, and livelihoods. *Conservation Biology* 23: 520-530.

Xu J and Grumbine RE (2014) Building ecosystem resilience for climate change adaptation in the Asian highlands. *Wiley Interdisciplinary Reviews: Climate Change* 5: 709-718.

Yao Y and Zhang B (2015) The mass elevation effect of the Tibetan Plateau and its implications for Alpine treelines. *International Journal of Climatology* 35: 1833-1846.

Zhang L and Fang JY (2004) Composition and dominant species of seed bank along an altitudinal gradient in Mountain Taibai, Qinling Mountains. *Biodiversity Science* 12: 123-130. [In Chinese.]

Zhang Y, Dai L, and Pan J (2001) The trend of tree line on the northern slope of Changbai Mountain. *Journal of Forestry Research* 12: 97-100.

Zhang Y, Wilmking M, and Gou X (2009) Changing relationships between tree growth and climate in Northwest China. *Plant Ecology* 201: 39-50.

Zhao F, Zhang B, Pang Y, et al. (2014) A study of the contribution of mass elevation effect to the altitudinal distribution of timberline in the Northern Hemisphere. *Journal of Geographical Sciences* 24: 226-236.

Zhao F, Zhang BP, Zhang S, et al. (2015) Contribution of mass elevation effect to the altitudinal distribution of global treelines. *Journal of Mountain Science* 12: 289-297.

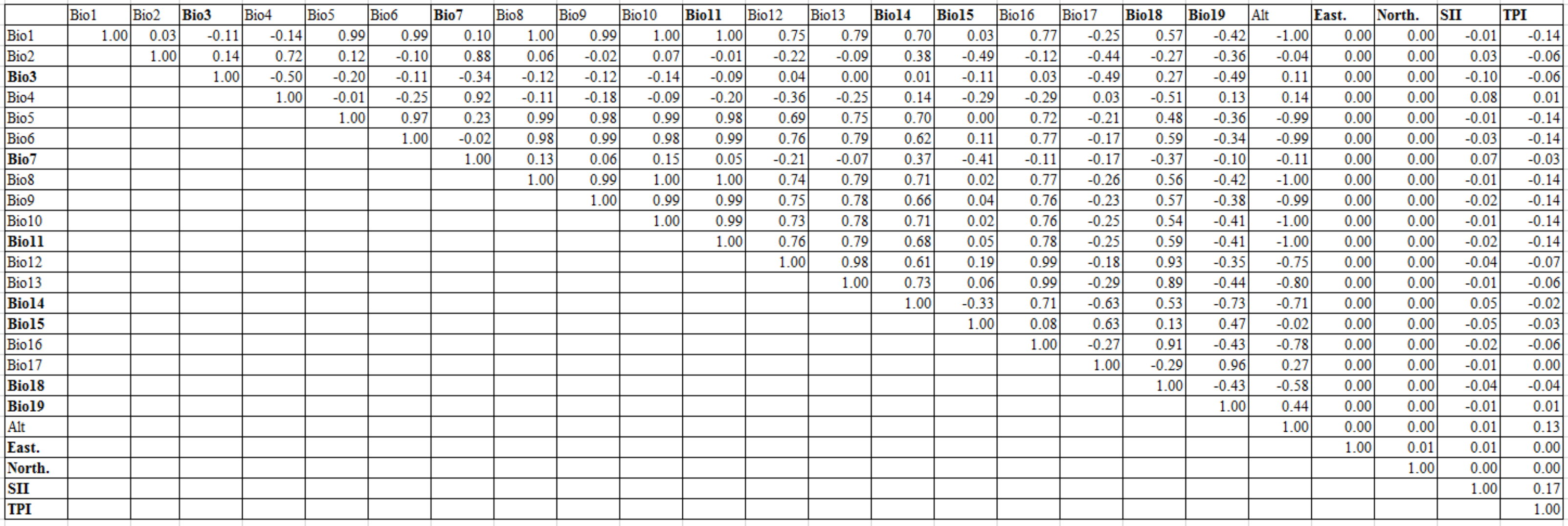
Zomer RJ, Trabucco A, Metzger MJ, et al. (2014). Projected climate change impacts on spatial distribution of bioclimatic zones and ecoregions within the Kailash Sacred Landscape of China, India, Nepal. *Climatic Change* 125: 445-460.

Zong S, Wu Z, Xu J, et al. (2014) Current and potential tree locations in tree line ecotone of Changbai Mountains, Northeast China: The controlling effects of topography. *PLoS One* 9: e106114.

APPENDIX I: TOPO-CLIMATIC VARIABLES USED IN THE MAXENT MODEL

Variable code	**Variable type**	**Data Source**	**Resolution**	**Range and mean**
BIO1	Annual mean temperature	WorldClim	30 arc sec (~1 km)	-16.6 – 24.8 (14.0 °C)
BIO2	Mean diurnal range: mean of monthly (max temp–min temp)	WorldClim	30 arc sec (~1 km)	6.4 – 14.3 (11.1 °C)
BIO3	Isothermality: (bio2/bioP7)*100	WorldClim	30 arc sec (~1 km)	3.8 – 5.1 (4.4%)
BIO4	Temperature seasonality (SD*100)	WorldClim	30 arc sec (~1 km)	3527 – 6089 (4821)
BIO5	Maximum temperature of warmest month	WorldClim	30 arc sec (~1 km)	-4.9 – 39.0 (25.1 °C)
BIO6	Minimum temperature of coldest month	WorldClim	30 arc sec (~1 km)	-32.3 – 11.1 (3.9 °C)
BIO7	Temperature annual range (BIO5–BIO6)	WorldClim	30 arc sec (~1 km)	16.2 – 31.2 (24.7°C)
BIO8	Mean temperature of wettest quarter	WorldClim	30 arc sec (~1 km)	-10.0 – 29.5 (18.7 °C)
BIO9	Mean temperature of driest quarter	WorldClim	30 arc sec (~1 km)	-22.0 – 23.5 (8.6 °C)
BIO10	Mean temperature of warmest quarter	WorldClim	30 arc sec (~1 km)	-9.7 – 30.8 (19.2 °C)
BIO11	Mean temperature of coldest quarter	WorldClim	30 arc sec (~1 km)	-23.1 – 18.1 (7.1 °C)
BIO12	Annual precipitation	WorldClim	30 arc sec (~1 km)	53 – 1234 (1373.1 mm)
BIO13	Precipitation of wettest month	WorldClim	30 arc sec (~1 km)	301 – 4446 (358.9 mm)
BIO14	Precipitation of driest month	WorldClim	30 arc sec (~1 km)	0 – 22 (5.72 mm)
BIO15	Precipitation seasonality (coefficient of variation)	WorldClim	30 arc sec (~1 km)	54 – 135 (99.7 mm)
BIO16	Precipitation of wettest quarter	WorldClim	30 arc sec (~1 km)	140 – 3239 (892.9 mm)
BIO17	Precipitation of driest quarter	WorldClim	30 arc sec (~1 km)	5 – 104 (45.5 mm)
BIO18	Precipitation of warmest quarter	WorldClim	30 arc sec (~1 km)	122 – 3239 (743.6 mm)
BIO19	Precipitation of coldest quarter	WorldClim	30 arc sec (~1 km)	5 – 182 (67.7 mm)
DEM	Elevation	DIVA GIS	30 arc sec (~1 km)	61 – 8384 (2104 m)
Eastness	Eastness	DEM	30 arc sec (~1 km)	-1 – 1
Northness	Northness	DEM	30 arc sec (~1 km)	-1 – 1
TPI	Topographic position index	DEM	30 arc sec (~1 km)	-573 – 939 (0.12)
SII	Solar illumination index	DEM	30 arc sec (~1 km)	0 – 113 (12.8)

APPENDIX II: CORRELATIONS AMONG DIFFERENT TOPO-CLIMATIC VARIABLES.



	Bio1	Bio2	**Bio3**	Bio4	Bio5	Bio6	**Bio7**	Bio8	Bio9	Bio10	**Bio11**	Bio12	Bio13	**Bio14**	**Bio15**	Bio16	Bio17	**Bio18**	**Bio19**	Alt	**East.**	**North.**	**SII**	**TPI**
Bio1	1.00	0.03	-0.11	-0.14	0.99	0.99	0.10	1.00	0.99	1.00	1.00	0.75	0.79	0.70	0.03	0.77	-0.25	0.57	-0.42	-1.00	0.00	0.00	-0.01	-0.14
Bio2		1.00	0.14	0.72	0.12	-0.10	0.88	0.06	-0.02	0.07	-0.01	-0.22	-0.09	0.38	-0.49	-0.12	-0.44	-0.27	-0.36	-0.04	0.00	0.00	0.03	-0.06
Bio3			1.00	-0.50	-0.20	-0.11	-0.34	-0.12	-0.12	-0.14	-0.09	0.04	0.00	0.01	-0.11	0.03	-0.49	0.27	-0.49	0.11	0.00	0.00	-0.10	-0.06
Bio4				1.00	-0.01	-0.25	0.92	-0.11	-0.18	-0.09	-0.20	-0.36	-0.25	0.14	-0.29	-0.29	0.03	-0.51	0.13	0.14	0.00	0.00	0.08	0.01
Bio5					1.00	0.97	0.23	0.99	0.98	0.99	0.98	0.69	0.75	0.70	0.00	0.72	-0.21	0.48	-0.36	-0.99	0.00	0.00	-0.01	-0.14
Bio6						1.00	-0.02	0.98	0.99	0.98	0.99	0.76	0.79	0.62	0.11	0.77	-0.17	0.59	-0.34	-0.99	0.00	0.00	-0.03	-0.14
Bio7							1.00	0.13	0.06	0.15	0.05	-0.21	-0.07	0.37	-0.41	-0.11	-0.17	-0.37	-0.10	-0.11	0.00	0.00	0.07	-0.03
Bio8								1.00	0.99	1.00	1.00	0.74	0.79	0.71	0.02	0.77	-0.26	0.56	-0.42	-1.00	0.00	0.00	-0.01	-0.14
Bio9									1.00	0.99	0.99	0.75	0.78	0.66	0.04	0.76	-0.23	0.57	-0.38	-0.99	0.00	0.00	-0.02	-0.14
Bio10										1.00	0.99	0.73	0.78	0.71	0.02	0.76	-0.25	0.54	-0.41	-1.00	0.00	0.00	-0.01	-0.14
Bio11											1.00	0.76	0.79	0.68	0.05	0.78	-0.25	0.59	-0.41	-1.00	0.00	0.00	-0.02	-0.14
Bio12												1.00	0.98	0.61	0.19	0.99	-0.18	0.93	-0.35	-0.75	0.00	0.00	-0.04	-0.07
Bio13													1.00	0.73	0.06	0.99	-0.29	0.89	-0.44	-0.80	0.00	0.00	-0.01	-0.06
Bio14														1.00	-0.33	0.71	-0.63	0.53	-0.73	-0.71	0.00	0.00	0.05	-0.02
Bio15															1.00	0.08	0.63	0.13	0.47	-0.02	0.00	0.00	-0.05	-0.03
Bio16																1.00	-0.27	0.91	-0.43	-0.78	0.00	0.00	-0.02	-0.06
Bio17																	1.00	-0.29	0.96	0.27	0.00	0.00	-0.01	0.00
Bio18																		1.00	-0.43	-0.58	0.00	0.00	-0.04	-0.04
Bio19																			1.00	0.44	0.00	0.00	-0.01	0.01
Alt																				1.00	0.00	0.00	0.01	0.13
East.																					1.00	0.01	0.01	0.00
North.																						1.00	0.00	0.00
SII																							1.00	0.17
TPI																								1.00

Note: Variables highlighted in bold are used in the model. Bio 3 (isothermality), Bio 7 (temperature annual range), Bio 11 (mean temperature of coldest quarter), Bio 14 (precipitation of driest month), Bio 15 (precipitation seasonality), Bio 18 (precipitation of warmest quarter), Bio 19 (precipitation of coldest quarter), eastness, northness, SII, and TPI are the uncorrelated variables.

APPENDIX III: CLIMATIC VARIABLE RANGE AND MEAN VALUE IN CURRENT AND FORECASTED SCENARIOS

Climatic variables	**Variables range and mean**						
	Current climate	**Forecasted scenarios**					
		Lowest Emission (RCP 2.6)		***Stable Emission (RCP 6.0)***		***Stable Emission (RCP 6.0)***	
		2050	***2070***	***2050***	***2070***	***2050***	***2070***
BIO3	3.8–5.1 (4.4 %)	3.8–5.2 (4.5 %)	3.9–5.2 (4.5 %)	3.8–5.1 (4.4 %)	3.9–5.3 (4.5 %)	3.8–5.2 (4.4 %)	4.0–5.6 (4.7 %)
BIO7	16.2–31.2 (24.7 °C)	15.9–31.1 (24.1 °C)	15.6–31.0 (24.0 °C)	16.4–31.6 (24.6 °C)	15.4–31.3 (23.8°C)	16.5–32.2 (24.5 °C)	15.5–31.3 (23.4 °C)
BIO11	-23.1–18.1 (7.1 °C)	-21.2–19.7 (9.1 °C)	-21.2–19.8 (9.1 °C)	-21.0–19.8 (9.4 °C)	-19.9–20.9 (10.4 °C)	-20.2–20.5 (10.0 °C)	-18.6–22.0 (11.5°C)
BIO14	0–2.2 (0.5 mm)	0–2.7 (0.6 mm)	0–3.3 (0.3 mm)	0–4.4 (1.6 mm)	0 – 3.8 (1.7 mm)	0 – 2.6 (0.6 mm)	0–3.1 (0.7 mm)
BIO15	5.4–13.5 (9.9 mm)	5.4–13.0 (9.8 mm)	5.4–13.1 (9.8 mm)	3.8–12.6 (9.0 mm)	4.5–12.7 (9.3 mm)	5.9–13.6 (9.8 mm)	6..4–140 (10.1 mm)
BIO18	12.2–323.9 (74.3 mm)	16.7–330.1 (71.3 mm)	16.0–329.3 (74.7 mm)	11.1–328.8 (72.7 mm)	20.3–334.6 (67.1 mm)	17.0–477.1 (84.8 mm)	15.6–431.2 (97.6 mm)
BIO19	0.5–18.2 (6.7 mm)	0.9–19.8 (7.5 mm)	1.5–20.8 (8.0 mm)	1.3–18.9 (7.6 mm)	2.2–21.8 (9.7 mm)	0.6–21.8 (8.7 mm)	0.5–19.9 (7.4 mm)

Note: Trend of variables used in the model is presented only. Bio 3 (isothermality), Bio 7 (temperature annual range), Bio 11 (mean temperature of coldest quarter), Bio 14 (precipitation of driest month), Bio 15 (precipitation seasonality), Bio 18 (precipitation of warmest quarter), Bio 19 (precipitation of coldest quarter),