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Topography and human disturbances are major controlling factors in treeline pattern at Barun and Manang area in the Nepal Himalaya

Parveen K. CHHETRI[1]* http://orcid.org/0000-0001-8103-4541; e-mail: parveenkchhetri@tamu.edu
Krishna B. SHRESTHA[2] http://orcid.org/0000-0002-3548-0900; e-mail: krishnababu.shrestha@gmail.com
David M. CAIRNS[1] http://orcid.org/0000-0003-4110-196X; e-mail: cairns@tamu.edu

** Corresponding author*

1 Department of Geography, Texas A&M University, College Station, TX 77840, USA

2 UiB Global, Jekteviksbakken 31, PO Box 7800, 5020, Bergen, Norway

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Abstract: The alpine treeline ecotone is an important component of mountain ecosystems of the Nepal Himalaya; 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 and landscape scales. Therefore, we used Remote Sensing (RS), and Geographic Information Science (GIS) approaches to investigate cross-scale interactions in the treeline ecotone. Additionally, European Space Agency land cover map, International Center for Integrated Mountain Development (ICIMOD) land cover map, ecological map of Nepal, and United States Geological Survey Shuttle Radar Topography Mission-Digital Elevation Model were used to analyze treeline pattern at the regional scale. Digital Globe high-resolution satellite imagery of Barun (eastern Nepal) and Manang (central Nepal) were used to study treeline patterns at the landscape scale. Treeline elevation ranges from 3300-4300 m above sea level. *Abies spectabilis*, *Betula utilis*, and *Pinus wallichiana* are the main treeline-forming species in the Nepal Himalaya. 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 (Manang). Topography and human disturbance are the main treeline controlling factor in Barun and Manang respectively.

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Introduction

The treeline ecotone represents high elevation vegetation zones between closed continuous forest below and the treeless alpine zone above, and constitutes forest line (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 (Walsh et al. 2003; Butler et al. 2007), 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 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 forest line 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 special monitoring in the context of global climate change.

Himalayan alpine treeline ecosystems are vulnerable to global climate change, but have been little investigated. Only a few data are available on the treeline characteristics at regional and landscape scales from the Nepal Himalaya. Studies carried out so far (Gaire et al. 2014; Shrestha et al. 2014; Chhetri and Cairns 2015; Schickhoff et al. 2015; 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 we are 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 we mapped and analyzed treeline at the regional scale covering the entire Nepal, and that at the landscape scale focusing on Barun and Manang Valley.

1 Materials and Methods

1.1 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 147,181 km^2. The elevation ranges from 60 m above mean sea level (AMSL) in the south to over 8000 m AMSL in the north (Figure 1), which results 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 1) is located in the north of the Makalu Barun National Park (hereafter MBNP), Sankhuwasabha, east 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 AMSL (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 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 AMSL, and is dominated by *Pinus*

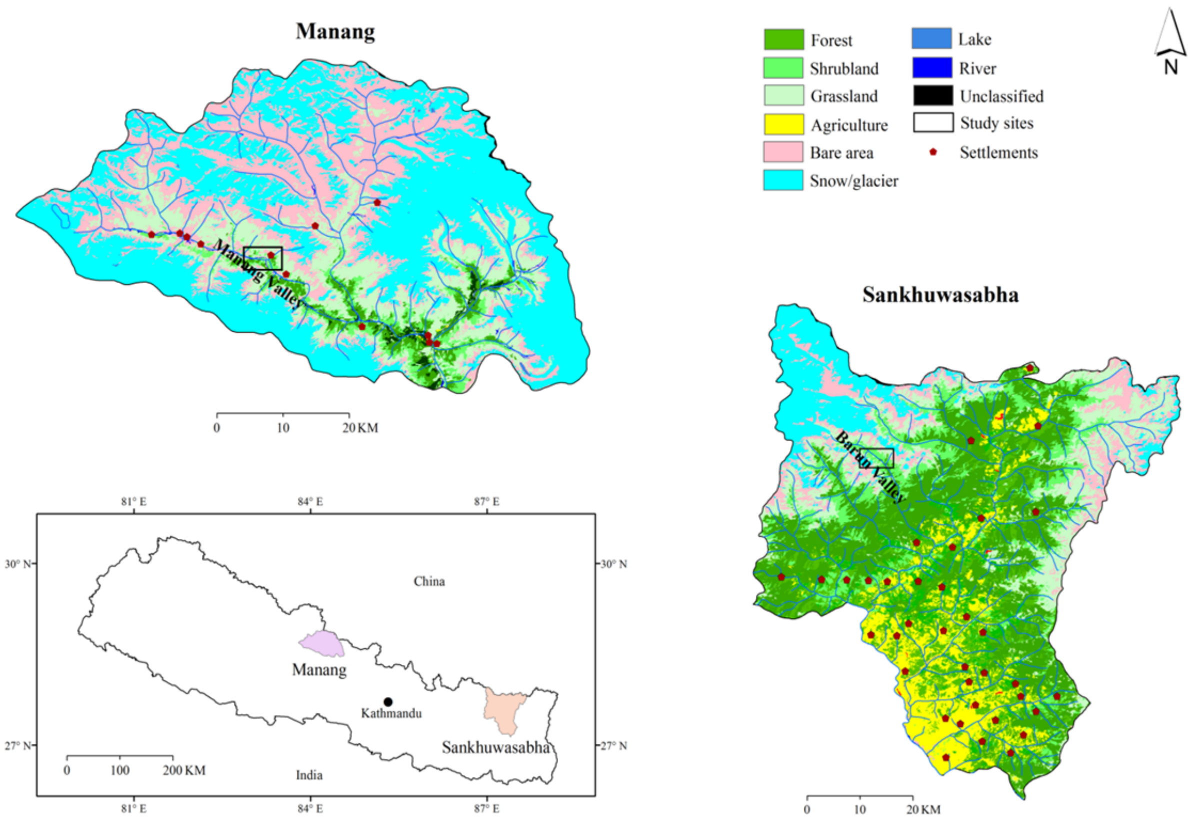

Figure 1 Study sites in eastern (Sankhuwasabha - Barun Valley) and central (Manang - Manang Valley) Nepal.

wallichiana (Himalayan blue pine), *Betula utilis* (Himalayan birch), and *Abies spectabilis* (Himalayan silver fir).

1.2 Treeline mapping and spatial pattern analysis

1.2.1 Regional scale

For mapping and analyzing the treeline at the regional scale, we 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; 30-m spatial resolution; Uddin et al. 2015) in 2010, and a GIS database of Nepal prepared by ICIMOD. We 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.

1.2.2 Landscape scale

Preprocessed high-resolution Digital Globe images 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 forest lines 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 forest lines and treelines were resampled to a 30-m resolution for further analyses. The DEM was used to assign the elevations of forest lines 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. We 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.

1.2.3 Possible biases in our analysis

We 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).

2 Results

2.1 Regional scale

Approximately 1800 km of treelines are mapped, and 80% of the field-based treeline observations matched the treelines generated here (Figure 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 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 m–4400 m AMSL (Figure 2). Treelines in eastern and western Nepal are at higher and lower elevations, respectively, than 4000 m AMSL. *Juniperus indica* formed the highest treeline in Nepal, with a mean treeline elevation of 4421 m AMSL (Table 1). No slope-exposure effect is observed at the regional scale treeline pattern (Figure 3). Average treeline elevation of south-, north- and other aspects are similar.

2.2 Landscape scale

Forest lines and treelines at the two study sites are presented in Figure 2. The overall accuracy of the mapping is 83% (Table 2). Results from mapping revealed that the mean forest line elevations are higher in Barun Valley than in

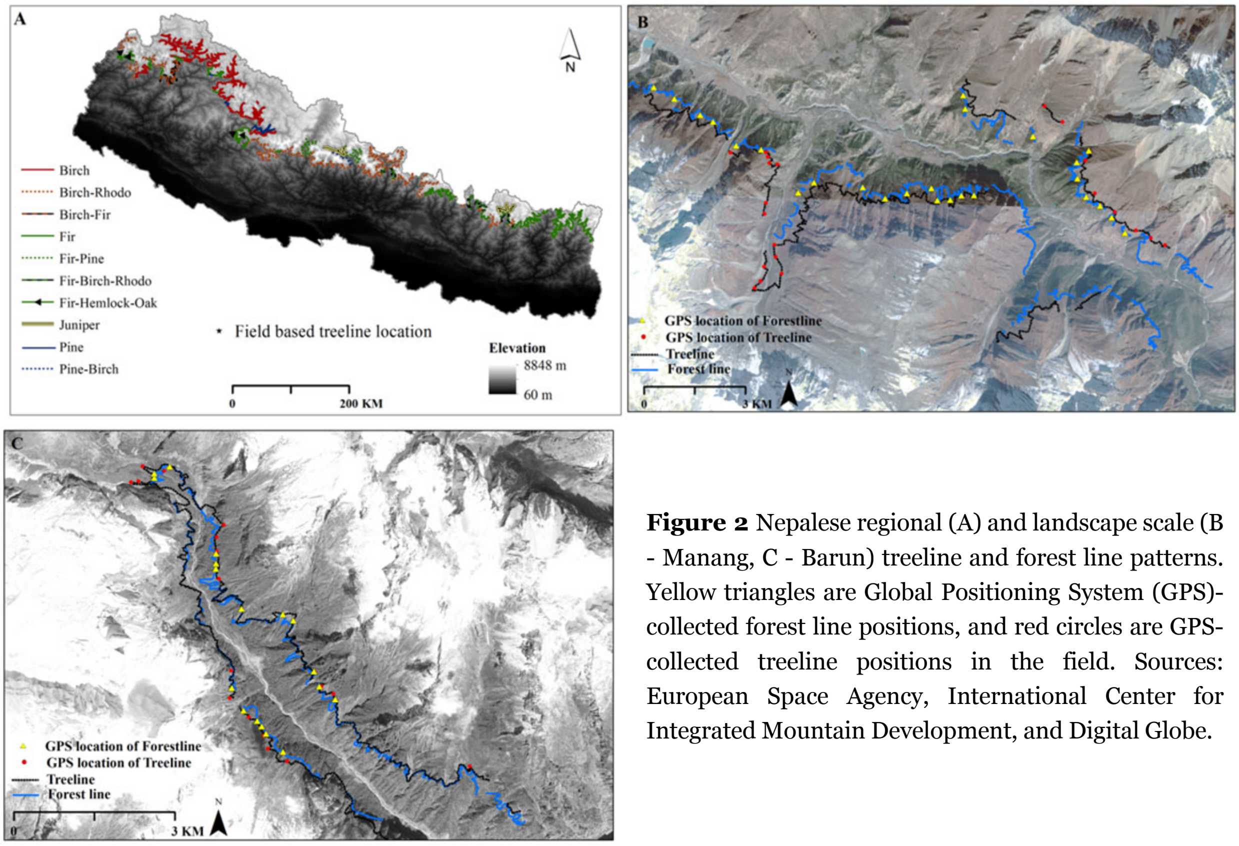

Figure 2 Nepalese regional (A) and landscape scale (B - Manang, C - Barun) treeline and forest line patterns. Yellow triangles are Global Positioning System (GPS)-collected forest line positions, and red circles are GPS-collected treeline positions in the field. Sources: European Space Agency, International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

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

Species	Mean treeline elevation (m AMSL)	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

Notes: AMSL = above mean sea level; Birch – *Betula utilis*; Rhododendron –*Rhododendron companulatum*; Fir – *Abies spectabilis*; Pine- *Pinus wallichiana*; Hemlock –*Tsuga dumosa*; Oak – *Quercus* spp.; Juniper – *Juniperus indica*.

Manang Valley (Table 3). However, the mean treeline elevation is highest in Manang Valley. The highest treeline elevation (4218 m AMSL) is recorded in Barun Valley. Mean treeline ecotone length is calculated as 8 m and 154 m in Barun and Manang valleys, respectively, and treeline 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). 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 4). South- facing slopes at all of the study sites have higher RRI values than north-facing slopes (Table 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 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 5). A small portion of Barun Valley treeline and major portion of south-facing slope of Manang Valley treeline is anthropogenic.

Table 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			
	Forest line	Treeline	Forest line	Treeline		
Forest line	17	3	24	0	41	82%
Treeline	3	17	0	21	38	84%
Field-based total	20	20	30	25	Overall accuracy: 83%	

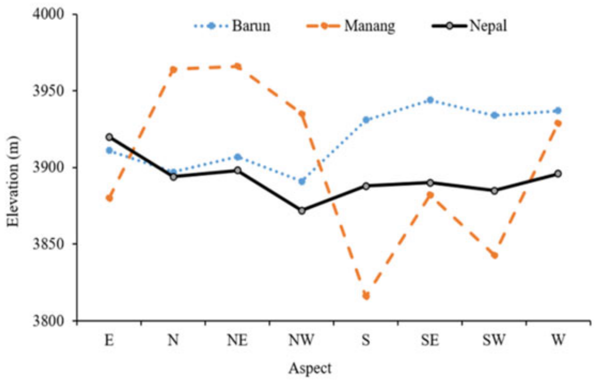

Figure 3 Mean treeline elevations at different slope exposures at two study sites and overall.

Notes: Aspect: N = North, E = East, S = South, W = West.

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

		Elevation (m AMSL)	
		Barun	Manang
Forest line	Highest	4201	4066
	Lowest	3574	3174
	Mean	3915	3773
	Standard deviation	86	175
Treeline	Highest	4218	4162
	Lowest	3687	3560
	Mean	3923	3927
	Standard deviation	94	113

Note: AMSL = above mean sea level.

Table 4 Relationships among treeline elevation, slope angle, and Relative Radiation Index (RRI)

	Barun			Manang		
	Elevation (m AMSL)	Slope (°)	RRI	Elevation (m AMSL)	Slope (°)	RRI
E	3911	28	0.75	3880	29	0.72
N	3897	31	0.51	3964	32	0.48
NE	3907	36	0.51	3966	29	0.59
NW	3891	19	0.71	3935	33	0.53
S	3931	30	0.96	3816	39	0.95
SE	3944	26	0.90	3882	29	0.89
SW	3934	37	0.88	3843	37	0.89
W	3937	30	0.78	3929	33	0.69

Note: AMSL = above mean sea level; Aspect: N = North, E = East, S = South, W = West.

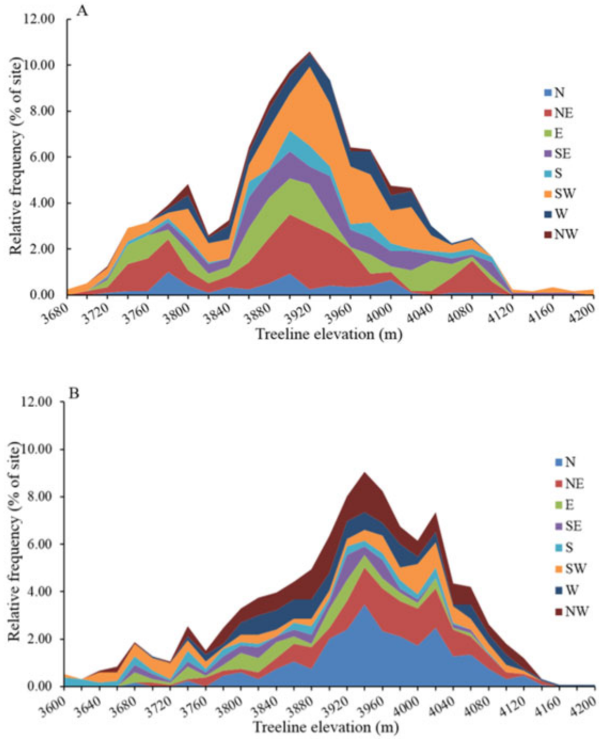

Figure 4 Frequency distribution of treeline elevations in respect to aspect at two study sites.

3 Discussion

3.1 Regional scale

This study has demonstrated the effectiveness of RS and GIS techniques for mapping forest lines and treelines. The results obtained from our regional mapping corroborate the information produced from other techniques (Schickhoff 2005; Gaire et al. 2014; Shrestha et al. 2014; Chhetri and Cairns 2015; Schickhoff et al. 2015; Chhetri et al. 2016; 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 AMSL 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).

3.2 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 our 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 our results are similar to those reported in these studies.

We 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) 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

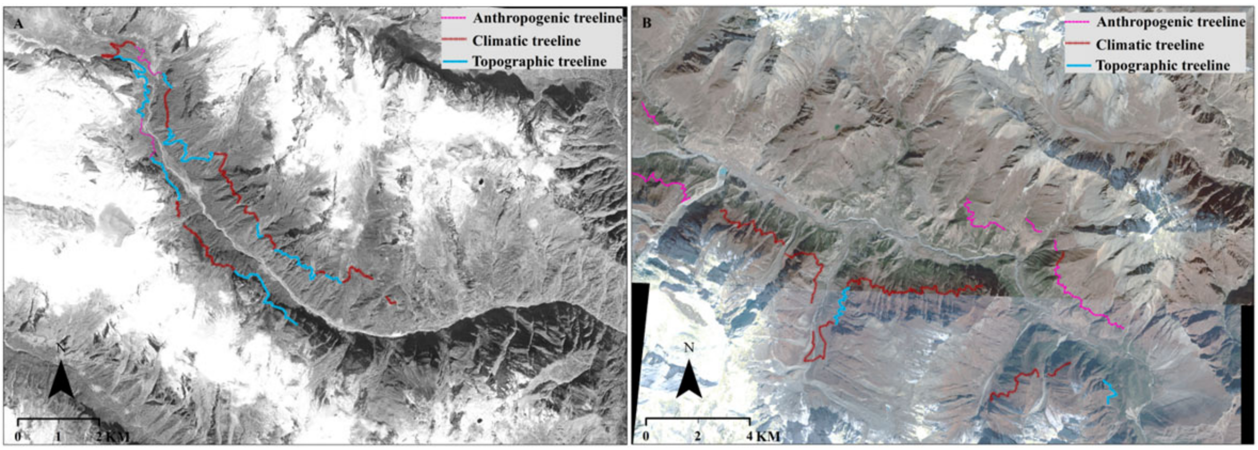

Figure 5 Treeline type (Anthropogenic, Climatic and Topographic) in A. Barun Valley and B. Manang Valley.

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.

4 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 indicated that topographic and anthropogenic treelines 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 forest lines and treelines to temperature changes. Future studies should investigate geomorphological and land use pattern near treeline, and treeline ecotone processes in order to understand treeline responses to environmental change in the Nepal Himalaya.

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