



Challenges of Timberline Mapping in the Himalaya: A Case Study of the Sikkim Himalaya

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Priyanka Sah, Avantika Latwal, and Subrat Sharma

Abstract

High-altitude Himalayan vegetation is considered a prominent indicator of climate change. Field-based observations are limited in coverage to understand regional patterns and to be used as inputs in ecological models for generalization. This study standardizes the terminology by defining the rules for the interpretation of timberline through auto-extraction methods and proposes a harmonized approach to regional-scale mapping of timberline by incorporating field-based observations. At rare locations in the state of Sikkim, high-altitude timberline may occur much below (~2620 m) or much higher altitude (~4390 m) than the normal range reported from field observations. Change analysis for timberline (upward or downward shift) in the Sikkim Himalaya indicates that the majority of the timberlines (76.5%) remained stationary in last three and half decades (1977–2015). The mean upward shift of timberline was $100 \text{ m} \pm 89$ (@ 2.71 m/year) and the mean downward shift was $56 \text{ m} \pm 54$ (@ 1.52 m/year). This study reports for the first time a stationary timberline in the Sikkim Himalaya, and the rate of change observed in this study is in tune with the previous studies. A well-harmonized approach, using satellite imagery in conjunction with field observations, can be useful for the regular monitoring of timberline change in order to study the impacts of global warming and biotic pressures at high altitudes.

Keywords

Change detection · Himalayas · Mapping · Timberline · Satellite Images

P. Sah (✉) · A. Latwal · S. Sharma

G.B. Pant National Institute of Himalayan Environment (NIHE), Ladakh Regional Centre, Leh, Ladakh (UT), India

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6.1 Introduction

High-altitude treelines and timberlines have gained global attention as a barometer for climate change in the last few decades. In high mountains, trees at their upper altitudinal limit make a conspicuous vegetation boundary. In this respect, two terms, timberline and treeline, are most commonly used. Timberline (or forest limit) is the maximum elevation of forest with cover at least 20–40%. Treeline refers to the transition from forest to treeless vegetation. It is defined as the connection among the highest-elevation trees (Singh and Rawal 2017). Studies from different parts of world show that warming is promoting vegetation or species richness in the alpiners, which means that higher the temperature, greater is the richness (Hamid et al. 2020; Holzinger et al. 2008; Lenoir and Svenning 2015; Dolezal et al. 2016; Lamprecht et al. 2018; Steinbauer et al. 2018). Across the mountains on the Earth, altitudinal shift in the occurrence of tree species has been attributed to different ongoing natural or anthropogenic processes and interactions of landscape elements (Kullman 2007; Germino et al. 2002; Ives and Hansen-Bristow 1983; Leonelli et al. 2009, 2016; Motta et al. 2006; Tremblay and Banas 2008; Colombaroli et al. 2010; Smith et al. 2009; Holtmeier and Broll 2005, 2007; Vittoz et al. 2008; Baker and Moseley 2007; Sarmiento and Frolich 2002; Singh et al. 2019).

Observations of many field biologists have paved the way for regional- or global-scale generalization for the formation of treelines and timberlines (Körner and Paulsen 2004; Schickhoff 2005; Berdanier 2010), but the Himalayan ranges pose a challenge for such global generalization. For example, the globally latitudinal decrease in timberline elevation in the Northern Hemisphere is distributed between the high peaks and terrains of the Himalaya. Based on some studies (point dataset), models have been developed to explain the relationship of treeline/timberline occurrence with geography, climate and their combinations (Zhao et al. 2014). Such field point observations have limited coverage in developing an understanding of local/regional patterns. Even studies on extensive field monitoring to realize the responses of vegetation are few (Kullman 2007; Germino et al. 2002), and a regional-scale model for the Himalaya is not available to explain timberline elevation and influence of geography. Such limitation is largely due to the inaccessibility of high-altitude terrains where field observations are not possible, hence a complete picture is always missing to realize a synoptic view, and in developing a complete geo-spatial database of high-altitude treeline/timberline. Details are required to determine the timberline elevations (Beaman 1962) for better predictions and modelling. Accurate remote sensing of mountainous forest cover change is important for myriad social and ecological reasons (Van Den Hoek et al. 2021). Timberline mapping through remote sensing techniques (Klinge et al. 2015) is a better way to realize the actual position of timberline in the mountains.

Mapping of the Himalayan timberline has started recently with an aim to understand the rate of migration of timberline (Bharti et al. 2012; Juntunen et al. 2002; Panigrahy et al. 2010a, b; Singh et al. 2012, 2018; Latwal et al. 2018; Mohapatra et al. 2019), and attempts have been initiated to develop a geo-database of regional timberline and analyse its relationship with topographical features (Sah and Sharma

2018; Singh et al. 2021a, b). Variability in terms of scale and methods in different studies makes it incomparable, and the actual shift in timberline remains debatable (Bharti et al. 2011). An evaluation of different remote sensing approaches for the highly rugged terrains of the Himalaya reveals that all methods do not perform adequately, and results may include methodological errors (Bharti et al. 2012). Thus, there is a need to adopt a uniformly applicable remote sensing approach for developing an ecologically compatible database of the Indian Himalayan Region (IHR) to assess timberline attributes at the regional scale, and its response to climate change and other factors. With this rationale, the chapter attempts to (1) standardize terminology for a regional-scale remote sensing-based mapping of timberline, (2) assess the role of scale in timberline mapping at regional (entire Sikkim state) as well as local scale (a watershed of the state of Sikkim) and (3) develop a methodological framework for a remote sensing approach to be applied for creating a comparable timberline geospatial database over the heterogeneous Himalayan landscape. It is expected that such a harmonized geospatial database will be a useful input for the regional modelling of change detection, future prediction and geographical explanations of diverse Himalayan timberline spread in about 2000 km length of these mountain ranges.

6.2 Study Area and Field Observations

High-altitude timberline in the Indian Himalayan Region (IHR) exists in five states/union territories, viz., Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh (arranged from west to east on the Himalayan Arc, Fig. 6.1). Sikkim and Arunachal Pradesh represent the north-eastern part and Uttarakhand, Himachal Pradesh and Jammu & Kashmir are in north-western part of the IHR. Because Sikkim is the smallest state, wide altitudinal variations, and a large area of protected area network in high altitudes were the criteria to take it as a test case to compare products (scale dependent) obtained from different satellite images and also to develop a methodological framework for evaluation and use. The state has four districts, namely East district, West district, North district and South district (Fig. 6.1), with district headquarters at Gangtok, Geyzing, Mangan and Namchi respectively.

High-resolution mapping was done in the Dzungri watershed where field surveys have been carried out for vegetation studies (Pandey et al. 2018a, b) in a part of the Khangchendzonga National Park. In the field study along the elevation gradient of 3000–4000 m, 23 tree species were recorded. In this altitudinal zone, only six species had a long elevation range (600 m or more, viz., *Abies densa*, *Pieris villosa*, *Acer caudatum*, *Sorbus thomsonii*, *Prunus rufa*, *Rhododendron hodgsonii*). Towards higher elevations (3800 m or above), different evergreen small tree/erect shrub species of rhododendrons were observed, viz., *R. hodgsonii* (3–7 m tall), *R. thomsonii* (3–5 m tall), *R. lanatum* (1–3 m tall), *R. wightii* (1–3 m tall) and *R. fulgens* (1–3 m tall). Above 3800 m, large trees of evergreen coniferous *Abies densa* (which can reach up to 60 m in height) along with deciduous tree elements, viz., *Acer*

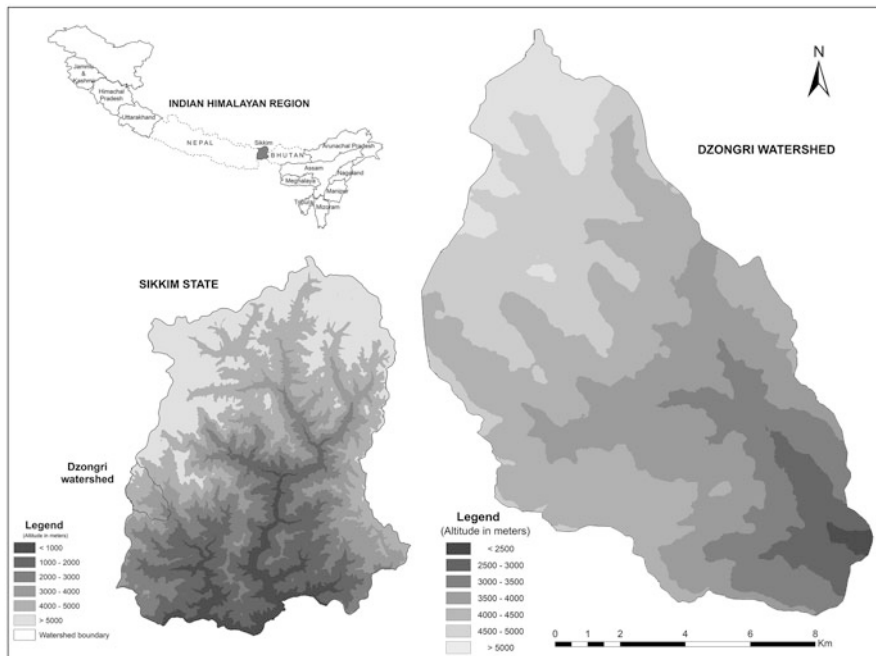


Fig. 6.1 Location of Sikkim State in the Indian Himalayan region and altitudinal profile of state and Dzungri watershed

caudatum (10 m tall), *Sorbus thomsonii* (8–10 m tall), *Prunus rufa* (5–6 m tall) and *Pieris villosa* (1–3 m tall) were observed. Information about plant height of tree species is based on description from e-flora (<http://www.efloras.org>). It appears that only a few large tree species occur in the high altitudes of Sikkim, and the total basal area of *Abies* forests or communities decreases with increase in altitude (52.5 m²/ha at 3200 m to 15.06 m²/ha at 3900 m; Pandey et al. 2018a).

In another study, Pandey et al. (2018b) reported that between 3790 m and 3990 m altitudes, the canopy tree layer was dominated by *Abies densa* and the under-canopy layer consisted of *Sorbus microphylla* and *Rhododendron lanatum*. At several sites, understory tree species were more prominent than *A. densa* or were sole tree species. At some sites, deciduous *Sorbus microphylla* and evergreen *Rhododendron lanatum* had higher densities than the canopy species *A. densa*. Interestingly this study in a narrow band of altitude (3790 m to 3990 m) recorded the presence of *Rhododendron arboreum* at this elevation, which was not documented in a previous study (Pandey et al. 2018a) at this high elevation, hence field-based studies may also provide different results. In these circumstances, diffused type of timberline exists, and the intermixing of different attributes of vegetation (short and tall height, coniferous and broadleaved canopy, evergreen and deciduous) may pose challenges in auto-extraction of information from satellite images.

6.3 Methodological Framework

Defining Timberline: Tree vegetation towards the high elevation is not a continuous feature and is disrupted by many factors. Realizing the heterogeneous appearance of vegetation in the landscape (Pandey et al. 2018a, b), the following rules were framed to draw a line on the map as timberline. (1) *Determining timberline*—up-slope termination of continuous forested landscape (canopy cover more than 30%; Singh and Rawal 2017) to alpine meadows (towards higher slopes) was considered timberline, (2) *Discontinuity in timberline*—disruption in the continuity of line due to large-scale geographical features and natural process (landslides, eroding soils, anthropogenic disturbances, rocks on higher slopes and their continuity towards permanent snow etc.) and (3) *Horizontal and vertical visualizations*—vertical sides of a forested landscape which faces the adjacent forested landscape on another slope were not considered as upper limit of trees (those drawn as limit of timberline in many studies). Otherwise, a lower altitude of timberline may be recorded than its normal occurrences. 3D visualization of the timberline was done by using DEM, so that the side edges of a forest were not confused with its topmost edge. This approach is much different from the indices-based mapping of timberline, and the line drawn in this study can be fairly considered the upper limit of the timberline in the study area (watershed and state).

6.3.1 Satellite-Based Observations

6.3.1.1 Selection of Appropriate Earth Observing Satellites

For developing a geo-database, mapping of timberline, and a regional synoptic perspective, satellite-based observation is most applicable technique. Satellite-based mapping in the higher Himalaya is a challenge where influence of local weather (local/monsoonal clouds or temporary snow cover over land surface) may obstruct the view of optical satellites and create confusion in the interpretation of various landscape features. Spatial resolutions in dominating 3D (folded) topography of mountains also pose challenges (hill shadows, steepness and analysis in 2D perspective) in realizing mapping objectives. High-resolution images are recent but consistency for comparison between decades is another issue. Use of high-resolution images to capture regional pictures of the object under study (timberline in this case) is also not economically feasible. Various satellite products which can be used in the Himalayan region are described by Ramachandran and Roy (2018). A high temporal resolution (few days) with technological consistency (instrument having same bands and resolutions) for a longer period (decades of operation) is a prerequisite in employing remote sensing approach towards (1) capturing various attributes of natural vegetation in the high altitudes and (2) analysing the impacts of natural factors and anthropogenic activities over a long period (change detection).

Keeping in view the tree heights and canopy dimensions of trees (Pandey et al. 2018a, b; www.eflora.org), use of satellite images with medium-range spatial resolution (20–30 m) appears suitable. Our search for instruments meeting all the above

criteria ended with (i) Thematic Mapper and its enhanced version (LANDSAT Series, NASA) and (ii) Linear Imagine Self Scanning System (LISS; IRS, ISRO).

We started with the LISS sensor (Linear Imagine Self Scanning System) of ISRO for the current period (1) LISS-IV series—spatial resolution of 5.8 m for revisit time of 5 days on one platform and (2) LISS-III series—spatial resolution of 23.5 m. Other details are given in Table 6.1. The presence of instruments on different platforms increased the temporal resolution of LISS products during overlap periods of different functional satellites (IRS-1C- 1996–2007, IRS-1D- 1998–2009, Resourcesat-1or IRS-P6- since 2003, Resourcesat-2- since 2011, Resourcesat-2A- since 2016).

Historical baseline records were developed from LANDSAT series of satellites those have consistency with bands and spatial resolution of 30 m (Table 6.1). The identified sensors were Thematic Mapper and its improved versions: Enhanced Thematic Mapper+ and Operational Land Imager. These sensors were on board from 1982 on Landsat 4, and were/are available on different platforms of subsequent satellites of the Landsat series (Landsat 5, 7 and 8). The operational overlapping period of different satellite missions makes more products availability on temporal scale. The revisit time is 16 days on one platform. After a thorough revision of various features of both the satellite series (IRS and Landsat), we finalized the products of TM/ETM+/OLI sensors for current timberline mapping and also to document historical changes in Himalayan timberline across the region (1977–2015) (difference of nearly four decades by availability of satellite data products). To check the influence of high resolution on local/regional-scale mapping, we used LISS-4 satellite images (spatial resolution of 5.8 m in multispectral) of recent years.

6.3.1.2 Challenges in the Himalayan Landscape and Mapping Season

The growing season in the high altitudes of Himalaya is limited to about 4 months, from May to September. Snowfall in winters, which extends beyond the permanent snowline, and clouds during the rainy season (June to September) are barriers to getting useful satellite scenes from the optical sensors. Options for usable images are limited to a narrow passage of season in a year. This is further restricted by the limited pass of satellites over the area in that narrow temporal window. Lush growth after rains does not provide much separation (mostly saturated) between tree canopy species but the onset of autumn and following the period before snowfall give an opportunity to separate deciduous from evergreen vegetation. The interpretation using these images of the pre-snowfall period can further be verified by the ground situation in spring. Leaf emergence and canopy development in deciduous trees vary considerably at the beginning of the growing season (spring onwards) in deciduous species. This attains maximum greenness during the rainy season; hence, images from the onset of autumn to the time when the area is snow covered are more appropriate. Keeping in view these characteristics, satellite images from October (Year 1) to January (following Year 2) were obtained.

Table 6.1 Spectral reflectance and spatial resolution of different sensors in a range of 20–30 m spatial resolution

Spectrum	Band				Wavelength (μm)				Pixel Size (m)				
	LISS-IV	L1/L2/L3 (MSS)	L4/5 (TM)/L7 (ETM +)	L8 (OLI/TIRS)	LISS-IV	L1/L2/L3 (MSS)	L4/5 (TM)/L7 (ETM+)	L8 (OLI/TIRS)	LISS-IV	L1/L2/L3 (MSS)	L4/5 (TM)/L7 (ETM +)	L8 (OLI/TIRS)	
Visible	B1			B1	–		–	0.43–0.45	–		–	30	
	B2		B1	B2	–		0.45–0.52	0.45–0.51	–		30	30	
	B3	B4	B2	B3	0.52–0.59	0.5–0.6	0.52–0.60	0.52–0.60	5.8	60 ^a	30	30	
	B4	B5	B3	B4	0.62–0.68	0.6–0.7	0.63–0.69	0.63–0.68	5.8	60 ^a	30	30	
Infrared													
		B6/B7	B4	B5	0.77–0.86	0.7–0.8/ 0.8–1.1	0.76–0.90	0.84–0.88	5.8	60 ^a	30	30	
Near													
			B5	B6	–		1.55–1.75	1.56–1.66	–	60 ^a	30	30	
Short Wave													
			B7	B7	–		2.08–2.35	2.10–2.30	–		30	30	
Middle													
			B6	–	–		10.40–12.50	–	–		120/ (30) ^b / 60	–	
Thermal													
TIRS 1			B10				10.6–11.19					30 (100) ^c	
TIRS 2			B11				11.5–12.51					30 (100) ^c	
Years	2003	1972/ 1975/ 1978	1982/ 1984/ 1999	2013									
		Panchromatic	B8					<i>Other Sensors</i>					
		Cirrus	B9			0.5–0.75		0.52–0.90	0.50–0.68	5.8	15	15	
									1.36–1.39			30	

^a Original MSS pixel size was 79×57 m; production systems now resample the data to 60 m^b Band 6 was acquired at 120-m resolution, but products are resampled to 30-m pixels^c TIRS bands 10–11: collected at 100 m but resampled to 30 m to match OLI multispectral bands

6.3.2 Test Case

To map the current position of timberline, a thorough search was made to obtain appropriate satellite images covering the timberline zone of entire Indian Himalayan Region. We preferred the state of Sikkim because it is the smallest state and is usually covered in one satellite scene and therefore stitching of two images of varying atmospheric conditions is not required. Images were downloaded from the United States Geological Survey (USGS) portal (<https://earthexplorer.usgs.gov/>) for the year 2015, and the image of 28 December 2015 (OLI on Landsat, multi-spectral, spatial resolution of 30 m) was chosen due to maximum visual separability between different features and absence of fresh snow at high altitudes.

To compare with Indian satellite products, we also obtained high-resolution multispectral images of LISS-IV (spatial resolution 5.8 m, [www1.n.d.](#)) for the same year (2015) but could not get usable LISS-IV scenes covering the entire timberline zone of Sikkim. We were restricted to procure three different scenes of January (spread between 2012 and 2015) to cover the entire timberline zone, assuming that there will not be drastic changes in the vegetation. This comparison also provided an opportunity to realize improvement in mapping at different scales, that is, 1:50,000 (Landsat) and 1:12,500 (LISS-IV). A small watershed in the *Khangchendzonga* National Park (field studies on vegetation done by Pandey et al. [2018a, b](#)) was also selected to compare various outputs of different satellite images at local scale. In addition to the timberline drawn from Landsat and LISS-IV images, additional timberline was drawn using high-resolution data of WorldView-3 (spatial resolution; 1.24 m) of 11 November 2017 for the same watershed. A small portion of high altitudes was not covered on this date so another image of 13 January 2015 from the same source was taken to complete the local-level timberline mapping. To make true colour images of WorldView-3, layers of three multispectral bands (band 5; red, band 3; green, band 2; blue) were stacked.

6.3.3 Image Interpretation and Mapping of Timberline

For realizing the timberline on the map, layer stacking (Band 2, 3, 4, 5 and 7) of Landsat data was done to develop a false colour composite. Image enhancement techniques were used to improve the interpretability of the images. Various tools of ERDAS IMAGINE 2016 image processing software were used.

Realizing the complex heterogeneous landscape features at high altitudes and limitations of auto-extraction methods (Bharti et al. [2012](#)) in mountains, knowledge-based manual interpretation (visual) was preferred to delineate the timberline from the satellite scene. Working in Sikkim, Singh et al. ([2018](#)) realized that auto-extraction methods overlook/leave certain complex areas, which requires manual corrections. Visual interpretation appeared more appropriate in the mountains (rugged terrain), where complex topography (steep, including shadow) challenges auto extraction of features.

An interpreter was trained to read and correlate various features in satellite images (Landsat, LISS series and true colour images of WorldView-3). The interpreter visited the high-altitude field to understand the ground features, particularly the different types of vegetation and their appearance on satellite images. Inaccessibility in all the areas of high altitudes is a major issue in the Himalaya. Field-based researchers draw inferences on the basis of limited ground knowledge, while much more vegetation is present than what is seen/sampled during field visits. In this situation, true colour high-resolution satellite images (available on Google Earth) are a useful resource to support the interpretation. High-resolution natural colour satellite images of different seasons were used to validate inaccessible sites. Keeping in view the knowledge acquired from field visits and training on visual interpretation, a single person was assigned to work on all the images to visually develop the timberline and to maintain consistency in results. An isoline connecting the highest edge of the forests (highest edge of the forests towards the alpine, as defined in 6.3) was created as ‘timberline’. This line breaks at various places due to various reasons. These broken lines were termed as segments/fragments of the timberline.

6.3.4 Geo-Spatial Attributes

Topography (elevation and aspects) influences the presence and distribution of vegetation (Klinge et al. 2015). Topography controls the overall presence of timberline; therefore, various attributes (slope—to measure the steepness of the terrain, which influences the recruitment of trees; aspect—a proxy for moisture and temperature gradient on a given altitude; elevation—a proxy for air temperature along the altitudinal gradient) were developed for the entire state of Sikkim with the help of a digital elevation model (DEM). The ASTER DEM of same spatial resolution as that of satellite images (30 m) was obtained from the USGS portal (<https://earthexplorer.usgs.gov/>) to develop the relationship between the spatial characteristics of the timberline and the topographical features (altitude, slope and aspect). ArcGIS was used for various spatial analyses and the extraction of attribute data of the timberline. The generated data on timberline, using satellite images, was subjected to various statistical treatments and correlated with various spatial attributes (latitude, longitude, altitude, slope, aspect).

6.3.5 Delineation of Timberline and Change Analysis

Remote sensing is of utmost importance in delineating timberline and demonstrating the changes occurring in the Himalayan landscape. The long-term availability of Landsat (since 1972) makes it possible to realize spatio-temporal variability of timberlines at a larger scale.

In order to map the longest spatio-temporal dynamics of the timberline in the Sikkim Himalaya, Landsat 8 (OLI, path/row 139/041 acquired on 28 December 2015) and Landsat-2 (MSS, path/row, 149/041 acquired on 23 January 1977) were

used. A usable clear image of TM (Thematic Mapper) for Sikkim was available for 1989. Hence, for long-term change analysis, we also searched for MSS, where we faced again non-availability of suitable scenes for the Sikkim area from 1972 to 1976 (cloud cover more >50%, snow cover and stripping). The oldest required suitable scene was available in 1977. We opted to use this image, which was resampled at 30 m to make it comparable with the image of 2015. Different images were co-registered with the latest image of 2015 to do change analysis of the timberline. Spatial tools of ERDAS IMAGINE 2016 were used for these purposes (geometric correction, image enhancement, techniques etc.). The satellite images were then subjected to knowledge-based interpretation techniques and the timberline was delineated by applying visual interpretation. Changes in the timberline were recorded as a function of the shift in altitude from the past (1977) to the current (2015) position.

ArcGIS 10.5 was used for various spatial analyses and extraction of attribute data of the timberline. Following Sah and Sharma (2018), timberlines were further categorized on the basis of spatially distinct arrangements as (1) ‘*continuous*’ type (parallel to permanent snow line having the alpine region in between these two lines mostly in the inner Himalayan ranges [hereafter CTL]), and (2) summits with high elevations, away from the snowy ranges, arise due to geological processes where the island-type shape of the alpine zone occurs around the summit. Such alpine is surrounded by the timberline towards lower elevations, these types of timberlines were termed as ‘*island*’ type timberlines (hereafter ITL). These continuous line data (vector) were used to create point data (30 m separation between two points in a line) for the corresponding years (1977–2015) using the Pixel to ASCII Converter feature of ERDAS IMAGINE 16. Thirty-meter distance (spatial resolution) of points were in tune to resolution of ASTER DEM (30 m), which was used to extract altitudinal information. Points at every 30 m were generated over the entire timberline (past and present; ITL and CTL) to match the spatial attributes of DEM, and differences (elevation and distance) were recorded.

Temporal changes were marked as ‘shift’ (upward/downward) and ‘no change’ (stationary) in timberline position with respect to the base year (1977). The interaction of the line points and DEM provided the maximum altitude of timberline occurrence at each location. For each point of the timberline, spatial attributes (latitude, longitude and elevation) were extracted. These attributes were subjected to various statistical analysis.

6.4 Result and Discussion

6.4.1 Geo-Spatial Attributes of Sikkim

Sikkim is a typical mountainous state with preponderance of high elevation area (nearly 75% area above 2000 m amsl). Of the state’s total area, 21.3% is above the permanent snow line (above 5000 m, Fig. 6.1). Field observations on treeline/timberline in the eastern Himalaya illustrate its zone ranges from 3000 m to

4500 m (Singh et al. 2019; Schickhoff 2005; Chaudhuri 1992). Only 38.4% of the state falls in this altitude zone. Slopes are important features for the stabilization and recruitment of trees. Nearly 28% of the slopes in the state are gentle ($<20^\circ$) but mostly in the higher altitudes of the trans-Himalayan region. The middle part of the state has more steepness than other parts. Nearly 30% area of the state has slopes steeper than 35° . A negligible portion of the state can be considered flat topography (0.01%). Distribution of different mountain aspects ranged between 10.8% (north) and 13.9% (south-east). Cooler aspects (NW-N-NE) occupy nearly 40% of the total area.

6.4.2 Timberline in Sikkim and Its Geo-Spatial Characters

The timberline in Sikkim was mapped on various scales from different spatial resolution satellite images. For example, 1:50,000 using 30 m spatial resolution and 1:12,500 using 5.8 m spatial resolution for regional (Himalayan) and local-scale mapping were used, respectively.

6.4.2.1 Regional-Scale Mapping Using Spatial Resolution of 30 m

The timberline drawn for 2015 (derived from Landsat; 1:50,000 scale) is presented in Fig. 6.2. The entire timberline of the state (730.42 km) is between nearly 1° spread of latitude (27.24 to 27.89 N) and longitude (88.04 to 88.90 E). At rare locations of these mountains, high-altitude timberline may occur at a much lower (i.e. 2620 m) or much higher altitude (i.e. 4390 m) than the range reported by field studies from Sikkim. The lowest point of high-altitude timberline is usually not described in the field-based studies. Working on images of near resolutions in the same state, Singh et al. (2018) observed the highest treeline elevations at 4804 m for 2013 and 4579 m for 1977, while the mean was at 3542 m (2013). Such differences could be due to (1) different methods employed (auto-extraction followed by manual corrections in a past study and visual interpretation in the present case), (2) detection capability of different spatial resolutions (23.5 m and 77 m in a previous study and 30 m in this study), (3) source of elevation (CartoDEM vs ASTER DEM) and (4) definition of treeline or timberline (synonymous or antonymous).

The mean elevation of the entire timberline length was 3620 m amsl. Distribution of timberline was more apparent from 3000 m onwards and scarcely reaches above 4200 m. Nearly 60% of the total timberline of the state occurred between 3400 m and 4000 m altitude, and 27.4% of the timberline is present below 3400 m (Fig. 6.3). Altitude above 4000 m accounted for minimal presence of timberline (12.8%) in the state. Such details were not available previously.

The majority edge of high-altitude forests in Sikkim, that is, timberlines, occurs on gentle slopes (14% of total timberline on slopes less than 20°) or moderate mountain slopes (nearly half of the timberline, 49.2%, on slopes between 20° and 35°). With increasing steepness, the occurrence of timberline decreased (24.8% in $35-45^\circ$ and 12.2% in $>45^\circ$ slopes). Among the faces of a slope (i.e. aspects), the highest occurrence was observed on E-facing slopes (15% of the total timberline)

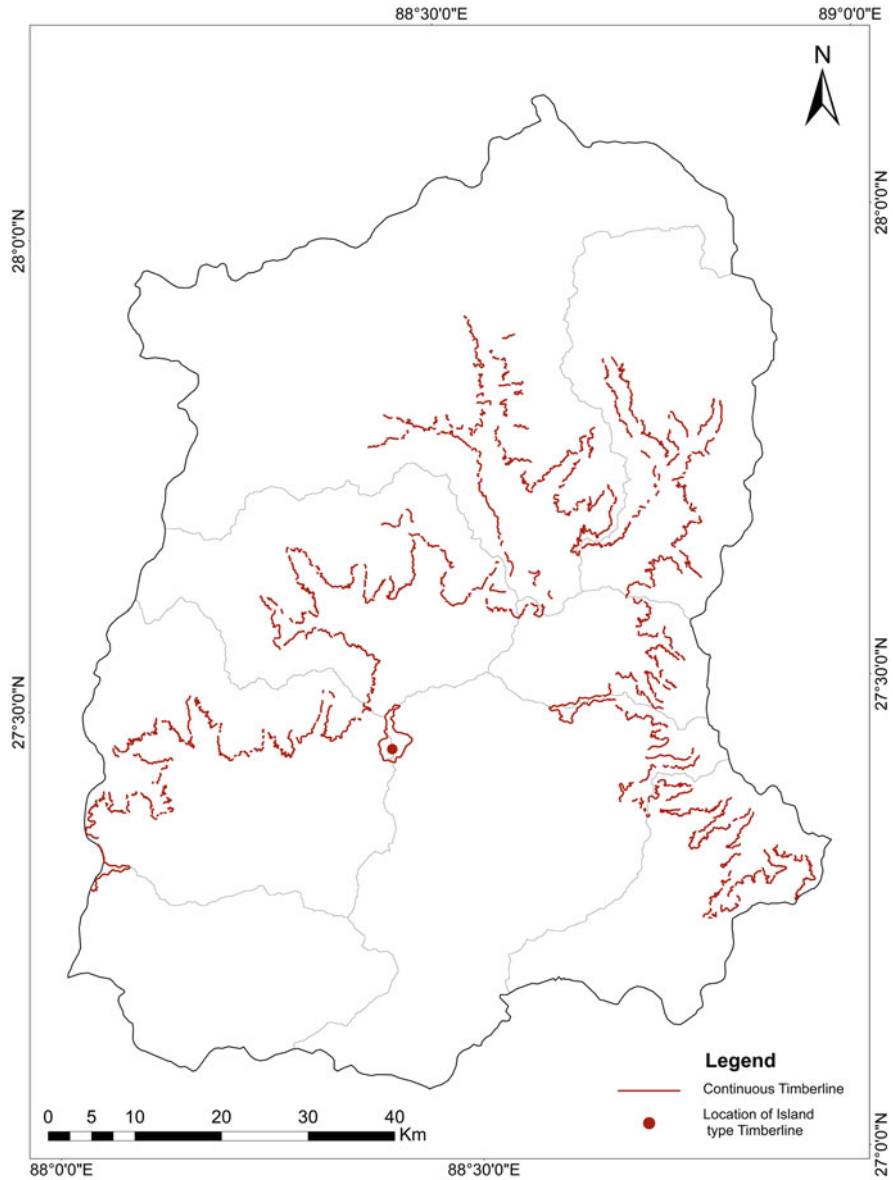


Fig. 6.2 Timberline drawn from Landsat image of 2015. Dot shows an isolated presence of timberline which is away from the main snow peaks

and the lowest on NW aspect (9.5%). On cooler aspects (NW-N-NE), 32.2% of the total timberline occurred, while the remaining was on warmer slopes.

The derived timberline was not a continuous line over its entire range. The timberline was fragmented due to various natural reasons (long stretches of rocks,

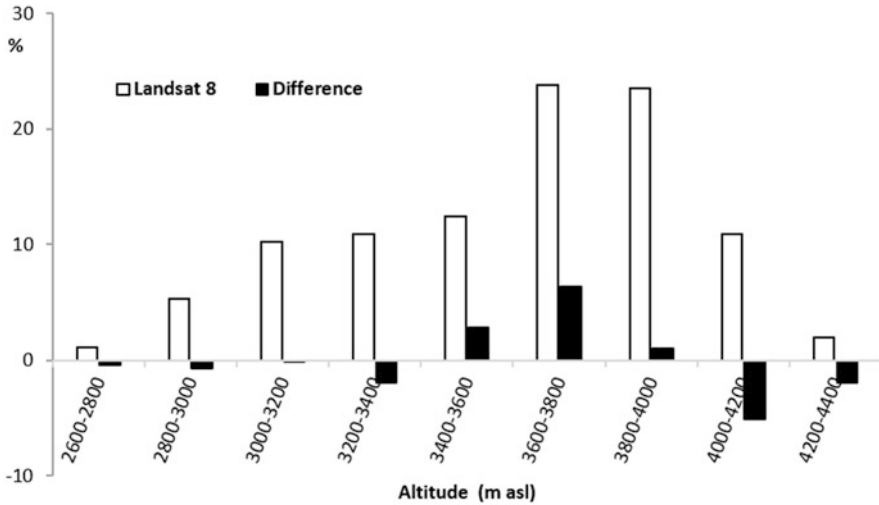


Fig. 6.3 Comparison of two spatial scales (Landsat 8 & LISS-4): Proportional distribution of total timberline length derived from two images of different resolutions in different elevational bands

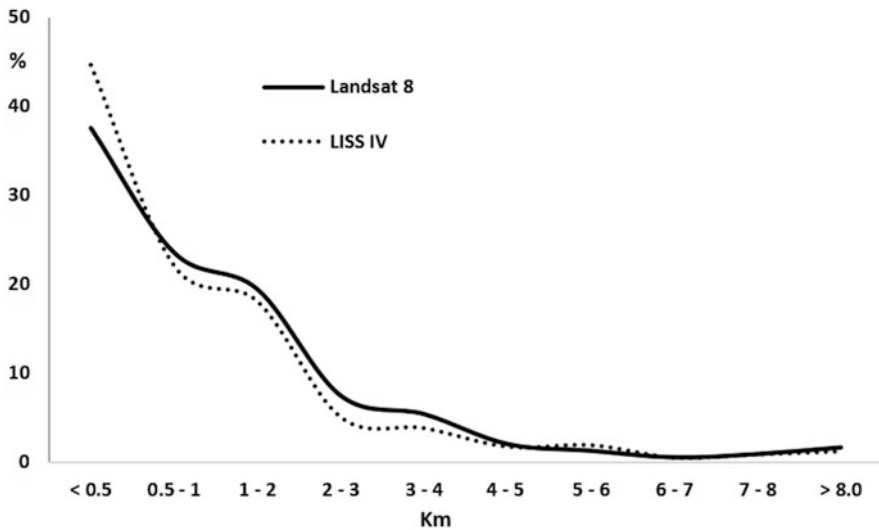


Fig. 6.4 Comparison of two spatial scales (Landsat 8 & LISS-4): Proportional distribution of number of timberline segments (arranged according to length) derived from two images of different resolutions

landslides etc.), and therefore, was divisible into 534 segments. The length of a timberline segment varied from 0.09 km to 19.98 km; however, more than one-third (37.6%) of the segments of timberline had a length below 500 m (Fig. 6.4). With increase in the length of timberline segments, the number of segments decreased,

and 34 segments (6.4%) had length 5 km or more (Fig.6.4). Mapping fragments (gaps between the timberlines) is important for understanding movements/shifts in upfront vegetation. In the absence of such details, misleading results may be obtained using automated methods (e.g. band ratioing, supervised classification etc.) for timberline shift.

A common belief regarding timberline presence in the Himalayas is that it exists parallel to the permanent snow line in the Himalayas, and the alpine zone lies in between these lines. We observed that the timberline may also exist around isolated summits where appropriate high altitude exists, termed as island type (Sah and Sharma 2018).

For the first time for the Sikkim Himalaya, we have mapped one such timberline (Fig. 6.2) which is not parallel to the permanent snow line (disjointed landscape from the Himalayan snow peaks). About 20 km of timberline was mapped with a minimum elevation of 2806 m and a maximum of 3436 m. Nearly 70% of this timberline falls between 3000 and 3400 m altitude and 8% lies above 3400 m altitude. Such geo-spatial details have been created for the first time and using visual interpretation method.

6.4.2.2 Local-Scale Mapping Using Spatial Resolution of 5.8 m, and Comparison with Regional-Scale Mapping

The total length of timberline derived from the mosaic of LISS-IV images was ~690 km (1:12,500), which decreased by 5.5% than the 1:50,000 scale. Many long segments were further divided due to better resolution, which resulted in 40 new timberline fragments. Thus, at this scale, timberline length was composed of 574 segments. Matching resolution between DEM and LISS IV (5.8 m) is not available; therefore, an elevational analysis was done with the present available DEM of 30 m resolution. A decrease in the elevational position of the timberline was also observed for both points of timberline's occurrence—lowest (down by ~10 m) and highest point (down by ~115 m). This indicates a complex terrain of high altitude requires fine-resolution satellite images for clear differentiation between features/classes; however, at a regional scale, such deviations are minor (entire altitudinal range of timberline has elevation difference of 1.6 km, i.e. from 2600 m to 4200 m).

The same is also evident from the distribution of timberline length in different altitudinal classes. The distribution pattern remains the same as in the case of regional mapping (1:50 K scale) but gain/loss in a category was substantial (Fig. 6.3). Nearly 70% of the total derived timberline at fine resolution (1:12.5 K) occurred between 3400 m and 4000 m altitude, which was 60% at the 1:50 K scale. An increase in the proportion of timberline was observed in three altitudinal bands (1% to 6.3%); however, towards both the tail ends of elevation band, the proportion of timberline decreased at the 1:12.5 K scale (Fig. 6.3).

In agreement with field-based observations (Pandey et al. 2018a, b), the maximum expression of timberline at both the scales remained highest in the same range of altitude (3600 m–4000 m) and the highest portion of occurrence in an elevation band was from 3800–4000 m at both the scales of mapping.

Total 48% of the timberline occurred on moderate slopes. The patterns of distribution on different slope categories were also changed at the 1:12.5 K scale where the proportion of timberline declined in gentle ($<20^\circ$; 13.2% of the total in comparison to 14% in 1:50 K) and moderate slope categories ($20\text{--}35^\circ$; 48%, compared to 49.2% in 1:50 K). On the contrary, a rise was observed in the categories with more steepness (25.7% of the total in $35\text{--}45^\circ$ and 13.2% of the total in $>45^\circ$ class) than 1:50 k. This further demonstrates that in rugged mountain terrains, finer spatial resolution images can perform better to separate diverse landscape features, which are confined in narrow zones. Among the slope aspects, the highest occurrence of timberline was continued on E-facing slopes (14.4% of the total timberline but lower than the 1:50 K), and warmer aspect of 'W' had almost similar proportion of timberline (13.9%, slightly higher than the 1:50 K). The NW aspect remained the lowest (10.6%) in terms of proportion of timberline, but slightly increased (1%) than the 1:50 K. On cooler aspects (NW-NNE), the proportion of timberline increased by 1% (33.9% of the total timberline).

6.4.2.3 Test Case of Watershed

At the watershed level (area 143.73 km², altitude range 2215–6084 m amsl; Fig. 6.1), the length of timberline mapped varied considerably between the source images, that is, 29.76 km (Landsat 8), 31.05 km (LISS-4) and 45.76 km (WorldView-3) (Table 6.2). Difference between 1:50 K and 1:12.5 K was only 4% increase in timberline length, while WorldView-3 images increased detailing of features and interpretation capability, hence timberline length increased 1.5 times over the length obtained from Landsat image. Using all the three satellite images

Table 6.2 Various attributes of timberline/treeline derived from different satellite images on watershed level and date generated from Field observations

Sl No.	Attribute	Present Study (Source Satellite Images)			Past Study (Singh et al. 2018)	Filed Study
		Landsat 8	LISS-4	WorldView-3	Landsat and LISS-3	
1	Maximum Altitude (m)	4095	4042	4073	4579 and 4804	4000 (Pandey et al. 2018a) 3787–3989 ± 4 (Pandey et al. 2018b)
2	Minimum Altitude (m)	3442	3347	3412	Not given	Not mentioned
3	Timberline Length (km)	29.76	31.05	45.76	Not given	Never measured
4	Segments (Number)	24	42	61	Not given	Not Known

maximum timberline elevation in this watershed increased between 40–95 m over the field studies conducted by Pandey et al. (2018a, b). Hence in inhospitable and inaccessible locations of Himalayan high altitudes, satellite image is useful tool to capture glimpses of tree vegetation. Minimum timberline elevation drawn from various satellite images was also comparable between Landsat (1:50 K) and WorldView-3 (1:3 K) image (3442 m vs 3412 m respectively), however due to hazy clouds in LISS-4 image interpretation was not clear at some places. Hence, elevation of timberline was decreased by 100 m over the other two images due to this misinterpretation. It appears that features of timberline elevations drawn at 1:50 K scale are comparable to finer scales if interpreted correctly with images of good quality. Interesting observation was that, with increasing finer spatial resolution of an image, number of timberline fragments was increasing (24 to 61) indicating that disruption in continuity in frontline tree vegetation towards alpine is frequent due to local features.

6.4.2.4 Changes in Timberline Elevations Between 1977 and 2015

The gain (32.7 km; increase) and loss (8.56 km; decrease) in different elevation bands were recorded since 1977, and the absolute increase in total length of timberline was about 23 km during the studied period. These changes occurred in less than one-fourth of the timberline length of 1977 (23.5% of total; 142.43 km upward and 23.8 km downward, Fig.6.5) while majority of the timberline (76.5%) remained stationary (i.e. no change) since 1977 (baseline data).

Mean elevation of the entire timberline in 2015 moved upward by 18 m since 1977; however, maximum elevation of occurrence remained same. Minimum elevation (lowest occurrence) increased by 79 m which indicates disappearance of lower end of timberline from unusual sites of occurrence.

We further analysed proportional distribution of timberline length in different elevational bands. It was realized that above 3600 m elevations there is gain in timberline length and below that elevation timberline is shrinking (3200–3400 m elevation). These finding suggests that high-altitude timberline may occur at any altitude in a given geography of the Earth, its response to natural factors is more visible in the favourable elevation zone in that regime. This zone is characterized by the location on the Earth (latitude, longitude and precipitation regime). For example, in Sikkim Mountains, maximum expression of timberline is between a zone of 400 m elevational difference (47.3% of the present timberline occurs between 3600 and 4000 m altitude) which has witnessed 75% of the total increase in timberline length in 37 years.

One more interesting observation was that entire timberline away from snowy ranges (Island type timberline, ITL) moved upwards where none of the segments remained stationary. It may be due to escape from more warming conditions in outer ranges in comparison to inner Himalayan ranges. ITL altitudes were warmer (average annual mean temperature $13.8\text{ }^{\circ}\text{C} \pm 0.7$) than the same timberlines altitudes of CTL ($8.6\text{ }^{\circ}\text{C} \pm 3.0$) by Latwal et al. (2022). Thus, outer Himalayan sites appear more prone to global warming, and to disturbances caused by anthropogenic activities (decrease in maximum elevation in 2015 may be attributed to later one). This is also

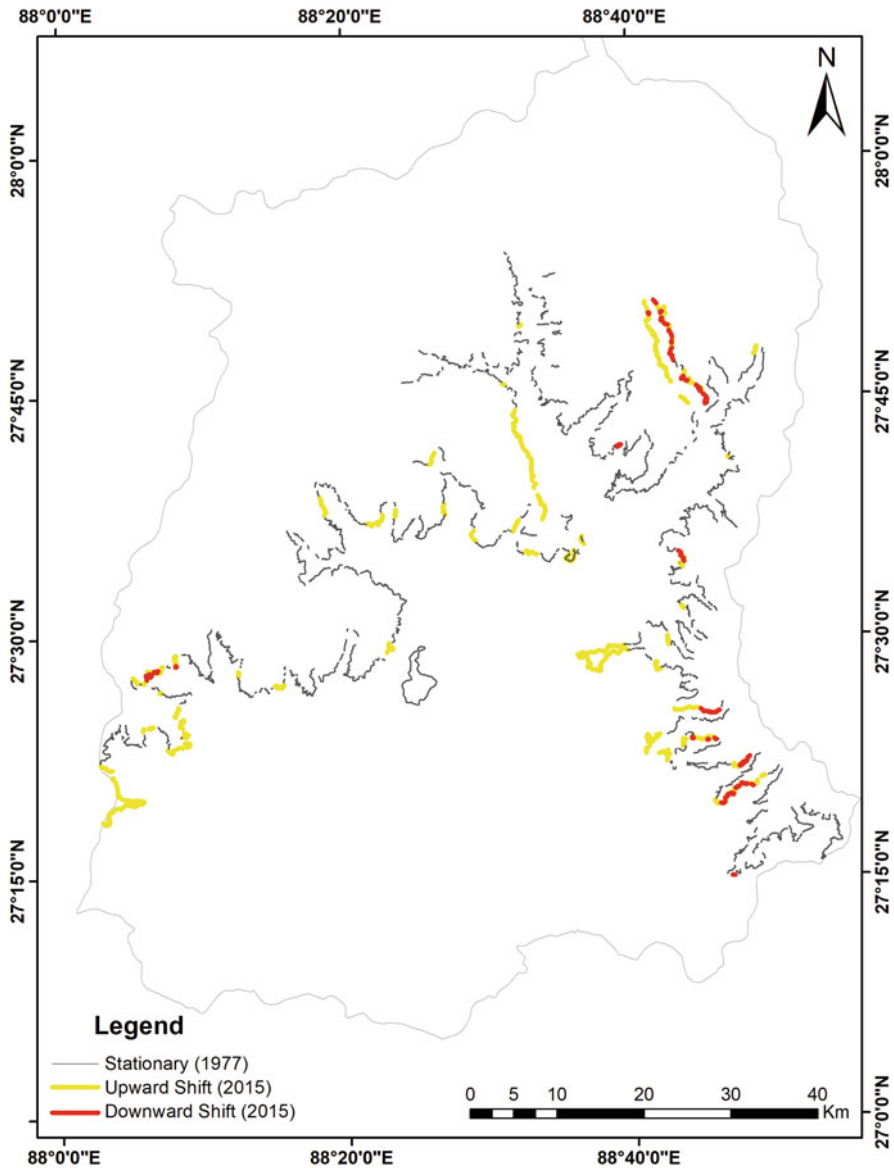


Fig. 6.5 The position of timberline in 1977 and 2015 in the state of Sikkim Himalaya

supported by the fact that minimum elevation of ITL increased by 43 m since 1977, and mean elevation increase of upwardly moved timberline was nearly 2.5 times greater in ITL (42 m) than the CTL (17 m). CTL increased by 22.9 km (3.3% of length in 1977) between 37 years of time frame with an increase of 79 m in minimum altitude while maximum elevation of occurrence remained same in this time period.

No expansion to upper limit may be attributed to non-availability of suitable sites in highest altitudes, which is characterized by poor or no soil cover and very low temperature, and occupied by largely permanent snow, glaciers, moraine and alpine meadows.

Detailed analysis of each timberline point (created at 30 m distance) shifted from its place (up or down) indicates that mean upward movement was $100 \text{ m} \pm 89$ since 1977 with an average rate of 2.71 m/year in 130 segments, while mean downward movement of various points was $56 \text{ m} \pm 54$ with an average rate of 1.52 m/year in 48 segments. More rainfall (high soil moisture) along with warmer conditions in Eastern Himalayan precipitation regime than the western Himalayan conditions increases probability of expansion of timberline ecotone due to developing warming conditions in the face of climate change, while landslide events due to same climatic conditions may erode timberline habitats at some locations bringing timberline elevation down.

6.4.2.5 Comparison with Previous Studies

Shift in treelines in the states of Uttarakhand, Sikkim and Arunachal Pradesh have been studied (Singh et al. 2012, 2018; Mohapatra et al. 2019). In nearly four decades (1977–2013) mean upward shift of treeline of Sikkim (eastern Himalaya) was recorded $301 \pm 66 \text{ m}$ (@ 81 m/decade), and in north-western Himalaya (Uttarakhand) it was recorded $388 + 60 \text{ m}$ (@ 114 m/decade) in three decades time period (1976–2006) while this was $452 + 74 \text{ m}$ (@ 113 m/decade) for alpine treeline ecotone of Arunachal Pradesh (1977–2013). Singh et al. (2021a, b) also reported a fundamental niche shift of c. 109.9 m/decade for Sikkim treeline (highest in Indian Himalaya) in response to climate change scenario (IPCC₅ RCP8.5 for year 2061–2080). For a part of Uttarakhand, Panigrahy et al. (2010a) reported an upward shift of timberline vegetation by 300 m between 1986 and 2004. On a repeat study of the same area on methodological issues, Bharti et al. (2011) concluded that remote sensing approaches require careful steps including selection of appropriate methodology and sufficient ground knowledge for such interpretations. From a dendrochronological study, in Himachal Pradesh, on a long-time scale (1860 to 2000), Dubey et al. (2003) concluded that the upward shift rate of treeline ecotone (dominated by blue pine, *Pinus wallichiana*) might vary from 14 m to 19 m decade⁻¹ on different aspects. Our study observed a rate (27.1 m/decade) close to these values in moist wet conditions of Sikkim Himalaya than the dry conditions of blue pine habitats in north-western Himalaya.

6.5 Conclusions

Remote sensing method can help to derive spatial attributes of timberline at regional/micro scale. Satellite images of high spatial resolution ($\leq 6 \text{ m}$) can improve timberline data (length and variation) by 10% over the medium spatial resolution (25–30 m) but availability of ‘useful’ high spatial resolution images is restricted by limited coverage, clouds etc., hence becomes a low priority in regional scale

mapping (viz., entire Himalayan timberline) and further non-availability of historical data restricts studies on impacts of climate change. However, spatial resolution refines certain attributes of object under investigation (e.g. timberline); consistent availability of medium spatial resolution images is useful to create scenarios on temporal scale (T_1 & T_2 , decadal etc.). Change analysis for timberline altitude (upward or downward shift) in the Sikkim Himalaya indicates that major portion of timberline (76.5%) remained stationary in last three and half decades (1977–2015) but mean elevation of entire timberline in the Sikkim Himalaya moved upward by 18 m due to changes in remaining 23.5% timberline. Both types of shifts (upward or downward movement) were observed at different locations with different rates. For example, mean upward shift was $100 \text{ m} \pm 89$ (@ 2.71 m/year) and mean downward shift was $56 \text{ m} \pm 54$ (@ 1.52 m/year). Rate of change is in tune with previous studies; however, stationary timberline from Sikkim is reported first time. A careful harmonized method, using satellite imagery, can be useful in regular monitoring of changes in Himalayan timberline to analyze impacts of climate change in high altitudes, particularly induced by global warming. Development of such harmonized geospatial database is useful input for regional modelling of change detection, future prediction and geographical explanations on the formation of diverse mountain timberline along the 2000 km long Himalayan arc.

This study highlights that there is need for spatial data-bank for the Himalayan region to monitor long term changes in biological processes (as timberline movement in this case) influenced by climate change or any other factors. Monitoring through satellites, having consistent and comparable products, may play a pivotal role in this regard.

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