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Topographical characterisation of high altitude timberline in the Indian Central Himalayan region

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Abstract: This study explores spatial patterns of timberline in the Indian Central Himalayan region (Uttarakhand State) to determine timberline elevations and its distribution across 22 watersheds. Characterization of spatial attributes of timberline based on topographical features was carried on. This study shows that remote sensing technique can be quite rewarding for capturing regional scenario on spatial distribution of timberlines. We could provide several new information on the spatial patterns of Indian Central Himalayan timberline. Firstly, the length of timberline is far longer than generally indicated by field sampling approach alone. In Uttarakhand it was 2750 km long within a crow flight distance of about one hundred km. Secondly, the segmentation of timberline due to immature topography and high tectonic activities is quite common. Thirdly, small timberlines enclosing small summits covered with alpine meadows are common feature in this part of Himalayas where forests grow up to considerably high elevations. In such cases climate warming is expected to drive the accumulation of species around the summits under the influence of global warming. Fourthly, it is long continuous timberline where much of the upward movement of plants would take place because of the availability of land areas between snowline and timberline. Such information about regional timberline will improve our understanding about influence of regional peculiarities on current positions and provide benchmark for assessing future shifts due to climatic changes and anthropogenic activities.

Key words: Central Himalaya, climate change, forest, mountain summit, timberline, topography.

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Introduction

The intensity of climate change is likely to be more severe towards higher latitudes and altitudes (McNeely 1990), where timberlines occur; hence they are among the most vulnerable systems to global climate change. Climatic timberline (based on local maximum elevation of existing forest stands; Körner & Paulsen 2004) is one of the fundamental ecological boundaries (Schickhoff 2005). The high altitude limits of forests are synonymously referred as treeline or timberline by various workers but are different. The treeline represents an ecological transition zone between fundamentally different low land and high altitude ecosystems (Mani 1978) which is a boundary or transition zone. Viewing from a distance, the ecotonal transition looks quite abrupt and is customarily regarded as a line (Shi & Wu 2013). Using satellite images or other remote sensing techniques certain canopy coverages can be mapped as treeline, and with GPS as treeline ecotone (Danzeglocke 2005; Singh *et al.* 2012).

Through satellite remote sensing effective monitoring (Baker *et al.* 1995) is possible for timberline resources and impacts of climate change

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on them. There is a need for satellite based mapping in the Himalaya because of their remoteness and difficult terrain. The highest treeline of the Northern Hemisphere occurs in Himalayan (Miehe *et al.* 2007). Field samples limited to a few places may not represent regional position of timberlines. Thus, sky-based measurements are necessary to detect the responses of timberline ecotone to the climate change at a regional level.

To find out advancement of timberline in the Himalayan region, use of remote sensing is a better choice over field based study (Bharti *et al.* 2012; Juntunen *et al.* 2002; Panigrahy *et al.* 2010a, b; Singh *et al.* 2012) but actual shift of timberline remains debatable (Bharti *et al.* 2011). Accurate determinations of timberline elevations (Beaman 1962) are desirable not only to know current position, but also for other reasons too- understanding of ecology of a species (distribution, tolerance range, comparative studies, etc.) and influence of geography (position and magnitude of controlling factors, and fluctuations therein).

Globally, timberline elevation decreases with latitude (Berdanier 2010) but latitudinal decrease of timberline elevation is not consistent as in mountain several other factors also influence it (Daubenmire 1954). In Europe, a study on Fennoscandian timberline indicates that factors other than climate such as "mountain mass elevation" and "summit syndrome" also affect timberline elevation (Odland 2015). This study explores spatial patterns of timberline in the Indian Central Himalaya to (i) determine timberline elevational range (lowest and highest) in relation to latitude, (ii) characterize the spatial attributes of timberline based on topographical features, and (iii) to find out distributional pattern of timberline in different watersheds, with and without permanent snow cover. An accurate estimation of regional timberline will improve our understanding about the influence of regional peculiarities on current positions and provide benchmark for assessing future shifts due to climatic changes and anthropogenic activities.

Study area

Indian Central Himalayan region (Uttarakhand State) occupies 53,483 km^2 geographical area between 28°43′N latitude and 31°28′N and 77°34′E and 81°03′E longitude. About 67% of the geographical area of the state is below 2500 m asl (Sharma & Phartiyal 2014), and forests occupy about 45% of the total area (FSI 2015). Altitudinal zonation of the state between 2500 m (lower limit of occurrence of high altitude forest types) and 4500 m asl (upper limit of forests) indicates that only 17% area of the state is available for forest types occurring in high elevations (Fig. 1), and 16.2% of the area in the state is above 4500 m asl which is occupied largely by permanent snow, glaciers, rocks, and moraines. From south to north mountain ranges can be classified as: (i) *Inner Himalaya* - permanent snow cover and adjacent high elevations of largely geological belts of 'Greater Himalaya' and in some part 'Trans Himalaya', (ii) *Outer Himalaya* - ranges, towards south, far away from Inner Himalaya having low or moderate elevations of Siwaliks and some part of Lesser Himalayan belt, and (iii) *Middle Himalaya* - in between Inner and Outer Himalaya moderate elevational ranges of largely Lesser Himalayan belt having abrupt high rising summits at few locations due to local geological faults. The drainage system is part of the *Ganga* river system to which various rivers and tributaries (snowfed and rainfed) originating from different watersheds contribute. The common timberline tree species are *Betula utilis, Abies pindrow, Quercus semicarpifolia*, etc (Rawal *et al.* 2018 in this issue).

Methods

Spatial data on timberline of entire Indian Central Himalaya was generated from maps developed using satellite images, and was subject to various statistical treatments.

Digital Data and Image Interpretation: Satellite images of Landsat 8 (multi-spectral, spatial resolution of 30 m) were used to generate a regional scale timberline (highest edge of the forest) mapping. Images were downloaded from United States Geological Survey (USGS) portal (https://earthexplorer.usgs.gov/) for the year 2015. Total five satellite scenes (georeferenced and orthorectified - UTM WGS 1984, zone 44) covered the entire region (Table 1). Satellite data were subject to layer stacking (Band 2, Band 3, Band 4, Band 5, Band 6 and Band 7) to develop False Colour Composite, and image enhancement techniques were applied to improve the interpretability of image. Various spatial tools of ERDAS IMAGINE 2016 were used for this purpose. The satellite images were then subjected to knowledge based interpretation technique and timberline was delineated by visual interpretation method. This method is more appropriate in mountainous conditions (rugged terrain of the Himalaya) where complex topography challenges auto extraction. An isoline connecting the highest edge of forests was

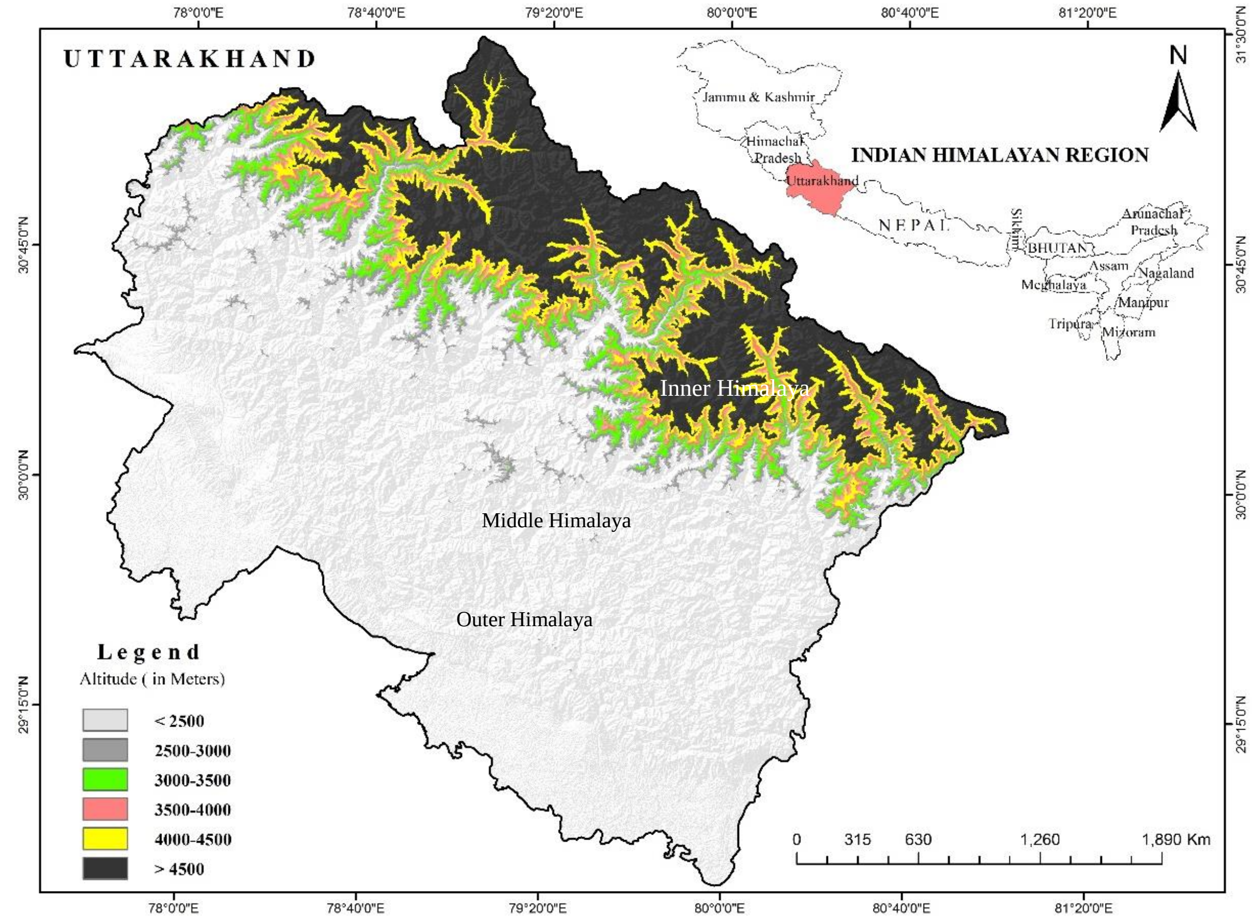

Fig. 1. Location map of Indian Central Himalaya (Uttarakhand) showing areas under different elevational bands above 2500 m.

Table 1. Landsat images used to determine the timberline of Indian Central Himalaya.

Date	WRS Path	WRS Row
2015/12/15	144	039
2015/11/20	145	039
2015/12/22	145	040
2015/12/29	146	038
2015/12/29	146	039

created as "timberline". This line breaks at various places due to natural factors (landslide, rocks, etc.). High resolution Google Earth™ images were used for the validation of inaccessible sites.

Spatial attributes and relationship with topography: Topography (elevation and aspects) influences the presence and distribution of vegetation in an area. Generation of various spatial statistics and development of relationships with topography were done on GIS platform using Digital Elevation Model (DEM) of the earth surface. DEM of ASTER having same spatial resolution as of satellite data, was obtained from United States Geological Survey (USGS) portal (https://earthexplorer.usgs.gov/). This DEM was used to develop relationship between spatial characteristics of timberline with topographical features namely altitude, slope, and aspect. DEM was used to delineate watersheds using GeoMedia Desktop 2016. Arc GIS was used for various spatial analyses and extraction of attribute data of timberline.

Results

Types of timberline and their spatial attributes

Watersheds in high altitude areas of this study generally consisted of forest, alpine meadows and permanent snow cover from lower to higher elevations. By definition, a timberline is upper edge of a forest with at least 30% crown density. A timberline generally took a course of line of many

A

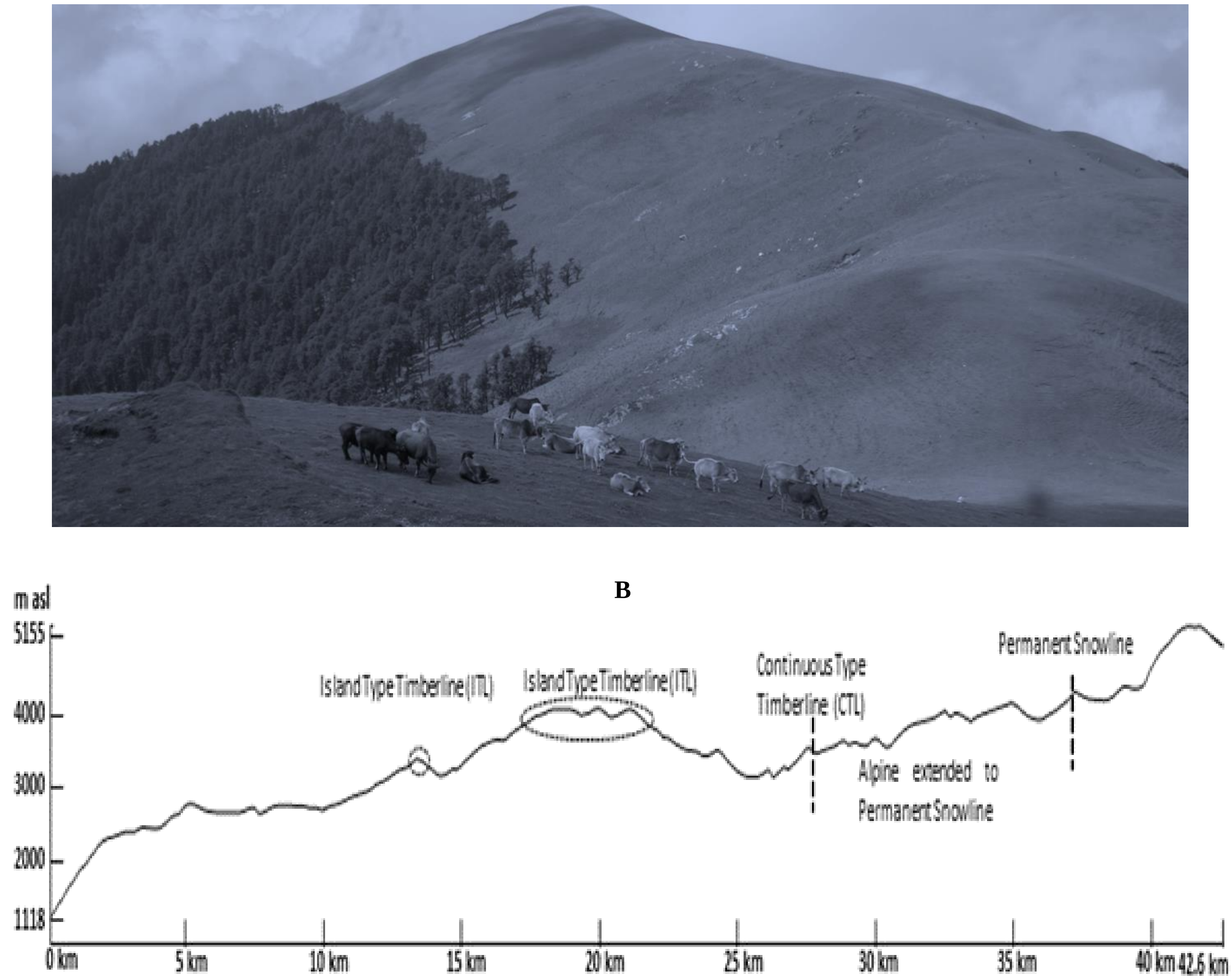

Fig. 2. **(A)** An isolated summit with an abrupt type timberline is made of *Quercus semecarpifolia*. The upper part is under alpine meadows, in lower part grazing livestock could be seen. **(B)** Sectional profile of a ridge running from river bed (1182 m) to altitude above 5000 m asl. Locations of two types of timberline (island and continuous), and permanent snowline are given.

miles in length parallel to permanent snowline, however, some timberlines encircled or enclosed small islands of alpine meadows near the summits in a relatively low elevation areas (Fig. 2A). In such cases summits are part of the alpine meadows. Here the first one is being referred to as continuous timberline (CT) and second one as summit enclosing timberline (SET) (Fig. 2B).

It may be pointed out that both timberlines were broken into several segments due to topographical barriers, but the segments of CT were long, often of tens and hundreds in kilometres. SETs were relatively shorter. Total length of timberline (sum of all pieces of the CT and SET types) in Uttarakhand was 2,750 km, of which CT type accounted for about 90%, and SET type, the rest. SET type occurred as isolated small circular and semi-circular fragments. The continuous type of timberline was like a long line broken only occasionally; the entire length of this was 2485 km, and it was broken into 91 segments, giving an average length of 27.3 km per segment.

The CT type timberlines traversed landscapes like a wave, moving up and down by several hundred meters within a few kilometres. Because it travelled along a zig-zag course, its total length was 7–8 times of the crow flight distance across the region, it occupied.

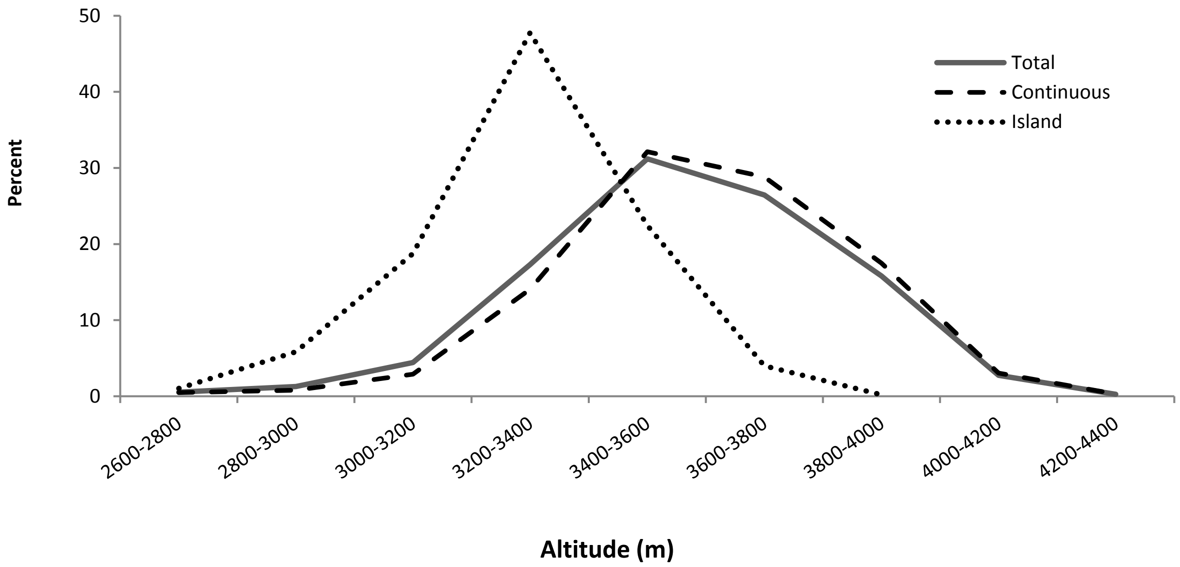

Fig. 3. Proportional distribution of timberline length along an elevation gradient. Percentage by elevational band of 200 m.

Distribution of total timberline length along the elevational gradient of about 1600 m (from 2600–2800 m elevation band to 4200–4400 m elevation band) showed a bell shaped pattern with peak (accounting for over one-third of the length) at 3600–3800 m (Fig. 3). The 3400–3800 m elevation range accounted for 57.6% of total timberline length of CT type. The peak distribution of SET type timberline was at a bit lower elevation band than continuous timberline type. Of the total length of SET type, about 61% occurred between 3400–3800 m.

The length of a continuous type timberline (CT) segment varied widely from 0.43 km to 388 km, and timberline became increasingly segmented towards higher side of elevation range because of increased topographical barriers and complexities.

In CT type the mean timberline elevation of segments (elevation of a segment varied along its length, hence a mean) ranged from 3215 m to 4020 m asl (Fig. 4). Distribution of timberline segments (as mean elevation timberline of segment) was as following- segment below 3500 m, 19%; between 3500 and 3600 m, 22%; between 3600 and 3700 m, 14%; 3700 and 3800 m, 22%; and above 3800 m asl, 23%.

Total length of SET, occurring at 32 different locations, was 265 km (Fig. 5). None of this type of timberline occurred above 4000m elevation. About 48% of 265 km occurred between 3200 m and 3400 m asl, and about 70% between 3200 and 3600 m, whereafter it sharply declined (Fig. 3). The length of SET at different locations ranged considerably from 0.55 km to ~60 km.

Distribution of timberline in relation to aspect and slope angle

Distribution of entire timberline with respect to aspect indicated that more of the timberline occurred on warmer aspects (SW = 14.3%, SE = 14%, W = 13.4%, E = 13.1%, & S = 12.6%; total 68%) than cooler aspects (N = 10.5%, NE = 10.9%, & NW = 11.2%; total 32%). The mean timberline elevations were generally higher on cooler aspects than the warmer aspects.

High Himalayan topography is very rugged and constituted by peaks and walls of watersheds, and valley floor. High altitude forests either creep into a valley floor or climbs to upslope on watershed boundary. Distribution of timberline in different slope categories indicates that trees have capability to grow on steep slopes, exceeding even 40°. Slope-wise distribution was as following: 17.7% of total timberline on gentle to moderate slopes (<20^{o}), and 27.7% on moderately steep slopes (20–30°), 27.7% on steep (30°–40°), and 26.9% on very steep slopes (> 40).

Spatial attributes of timberline in different watersheds

We delineated 22 watersheds from DEM within the region, of which in 15 watersheds timberline was

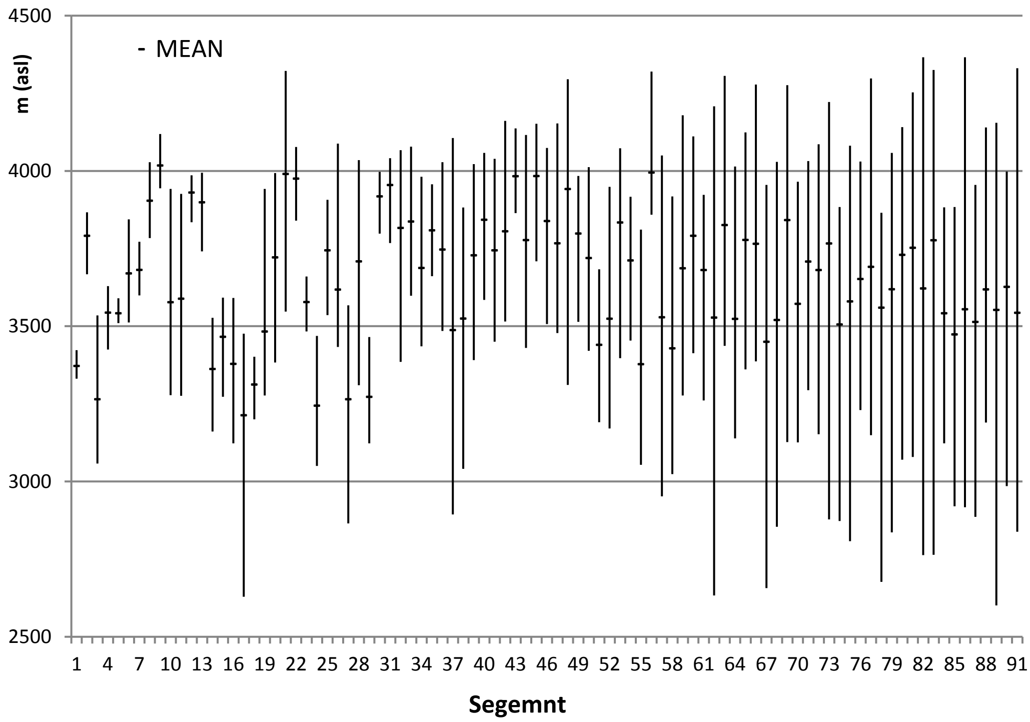

Fig. 4. Elevation range of a segment of continuous type timberline. Segments are arranged according to increasing length.

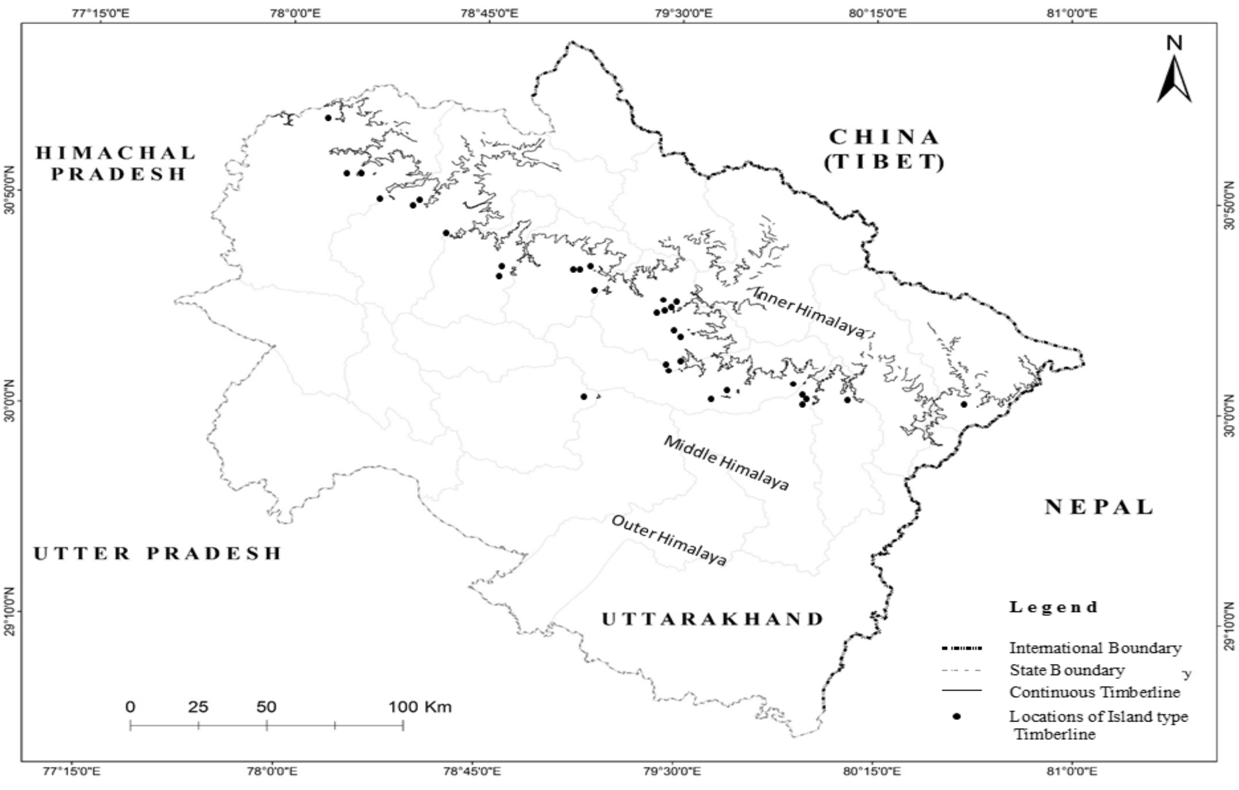

Fig. 5. Distribution of continuous and islands type (isolated pieces/dots) timberline in the Indian Central Himalaya. The island type timberline occupies relatively lower elevations.

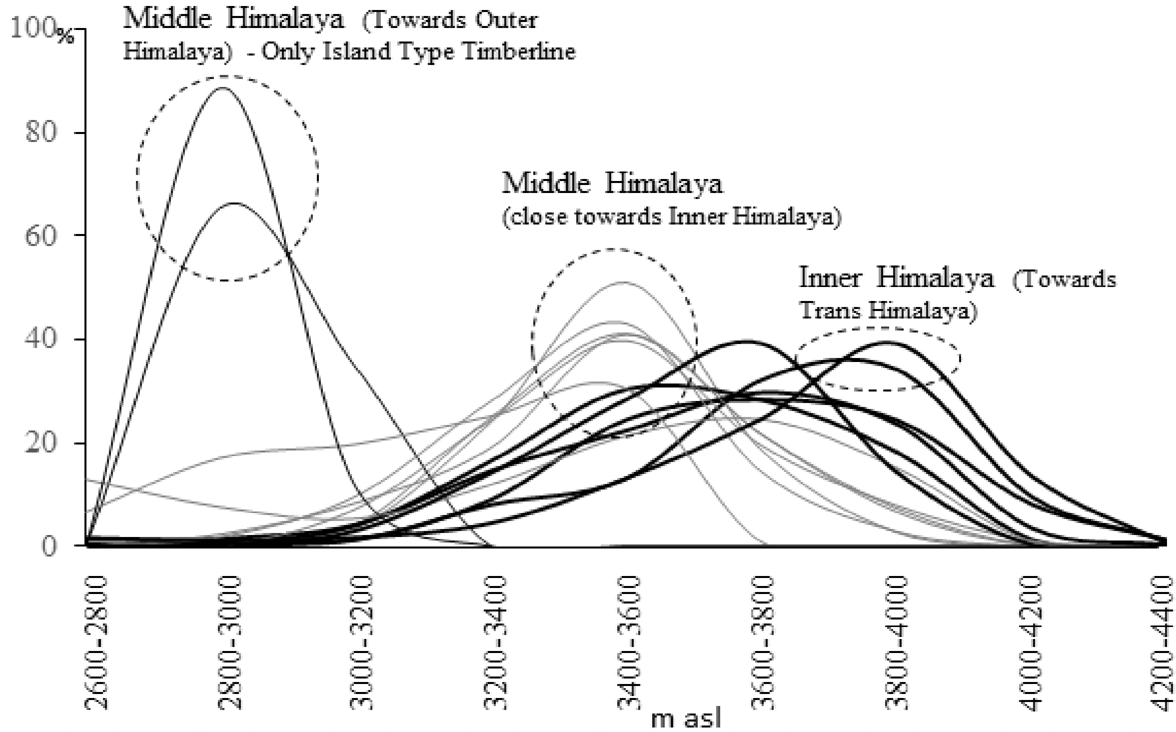

Fig. 6. Proportional distribution of timberline length by elevation bands (200 m) in study watersheds.

present (either one type or both types). Out of the 15 watersheds, four were without the permanent snowline, thus were largely rainfed. In two of such rainfed watersheds, CT was present which was running from the adjacent watershed (having permanent snow cover).

We infer from our timberline maps that the formation of CT type timberline requires the continuity of suitably high elevation over a fairly long stretch in a watershed. CT was present in that rainfed watershed which was adjacent to the snowfed watershed, but it was absent in that rainfed watershed which was adjacent to another rainfed watershed. In such rainfed watersheds only SET type was present. It is difficult to know whether the high elevation of watersheds with permanent snow cover simply provided suitable timberline elevation or its snow melt also facilitated tree growth.

Topography influenced the range of timberline elevation (TLE) in watersheds. Among the various watersheds, the minimum TLE ranged from ~2600 m to 3040 m while maximum TLE was between 3045 m and 4365 m. Among the different watersheds, mean TLE (mean of the watershed) ranged from 2930 m to 3755 m.

The elevation bands in which timberline occurred most varied across the study watersheds (Fig. 6). It was 2800–3000 m in two watersheds (I), 3400–3600 m in seven watersheds (II), 3600–3800 m in four watersheds (III) and 3800–4000 m in two watersheds (IV). These can be referred to as elevation centres of timberline. The timberline was centred in the lowest elevation band (I) in rainfed watershed of outer and Middle Himalayan ranges (see Fig. 5). In contrast, the highest timberlines were centred in snow-fed watersheds of inner Himalayan ranges (see Fig. 5).

Difference between lowest and highest timberline elevation within a watershed was between 145 m and 215 m in rainfed watersheds having only SET type timberline, while this difference in other watersheds ranged from 890 m to 1700 m.

SET was absent in three watersheds, and two (Sarswati and Dhauliganga) of these were located in the Inner Himalayan ranges where timberline elevation was the highest. The third watershed, Kaliganga (without SET), was a large watershed distributed both in Indian and Nepal, but the Indian portion (falling in the study area) was only 223 km^2 in Area.

It was observed that watersheds having more geological faults had more number of SET type timberline and higher segmentation in CT. In these high ranges geological disturbances account for the segmentation and isolated timberlines. These observations indicate that geological factors have a considerable role in giving shape to high elevation forests and timberline.

Discussion

This study shows that remote sensing technique can be quite rewarding for capturing regional scenario of timberlines. Unlike mountain timberlines of Europe and other such regions, in Himalayas they are high, remote and difficult to access. We could provide several new pieces of information on the spatial patterns of Indian Central Himalayan timberline. Firstly, the length of timberline is far longer than generally indicated by manual sampling. It is a major phyto-geographical feature, running across the region along a zig-zag course for 2750 km within a crow fly distance of a few hundred kilometres. Secondly, the segmentation of timberline due to immature topography and high tectonic activities is quite common. Thirdly, the presence of small timberlines enclosing small summits covered with alpine meadows is a common feature in this part of Himalayas where forests grow up to considerably high elevations. In such cases climate warming is expected to drive the accumulation of species around the summits under the influence of global warming. Fourthly, it is long continuous timberline where much of the upward movement of plants would take place because of the availability of land areas between snowline and timberline. Fifth, the elevational range of timberline even in a small geographical area can be clearly more than 1000 m. It would be interesting to know the patterns of timberline species distribution along such a length sunning across several watersheds.

More than half of the timberline length occurred between 3200 and 3600 m. This elevation band can be considered as 'timberline centre' for the Indian Central Himalaya, however TLE range was much wider. Two watersheds (Ganga and Yamuna) of the river Ganga contribute nearly 30% of the total timberline length of Uttarakhand, though they occupy only 16% of the total area of the state.

Apart from long continuous timberline, we identified an *island type timberline* (SET) around summits. SET was more in the Garhwal region of the state (27 locations) than Kumaun, indicating its more rugged and geologically broken terrain than the Kumaun region. Complexities of topographic features such as suitable elevation and availability of space (Latwal *et al*. 2018 in this issue), abrupt summits, steep slopes, and geographical placement (present study) influence the distribution of timberline in the region. Due to such spatial diversity, timberline species of the region may react in different ways to the changes due to climate and anthropogenic factors.

Aspect may influence species composition and structure of timberline (Danby & Hik 2007). An influence of topography and geology of the region is apparent on timberline elevation and location based shapes. Due to availability of suitable elevation, *Abies pindrow* forms timberline around two summits located within rainfed watersheds. These summits are located in the southernmost Himalayan ranges, and isolated like dots. Tree populations of these island type habitats are more vulnerable to impacts of climate change coupled with anthropogenic activities. Influence of human activities cannot be ignored, which lead to uncertainties in determining anthropogenic and climatic timberlines. This study along with observations of anthropogenic activities can be used as bench mark for such locations to detect any shift (in timberline elevations) in future.

Conclusion

Use of satellite images is promising technology to identify spatial attributes of timberline at a regional scale. This is the first study which describes spatial attributes and characterizes the Himalayan timberline on that basis. A comparison of the information generated with remote sensing method in this study with those derived from field sampling in mountains emphasizes that the latter gives not only a very incomplete picture of treeline, but also a distorted one. It seems that timberline elevation can exceed 4000 m in many parts of Himalayas, but they may be only exceptions. Our remote-sensed cartography shows that timberlines in Central Himalayas are centered between 3200–3600 m. Changes in the timberline centers would be more meaningful in the context of a region to document climate change impact than changes in one or two outliers. This study has created a framework to determine the impact of climate change in relation to the form of timberline, its elevation length and extent of isolation.

Island type of timberlines (SET) is important to monitor climate change impact, as they might be more sensitive in terms of changes in cover. They might act as nuclei around which future build up of vegetation may occur when heat deficiency is removed due to climate change. The study offers a method which could be used to analyze the pan-Himalayan distribution of timberline, and compare their sensitivities to climate change.

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