Monitoring the alpine treeline shift in parts of the Indian Himalayas using remote sensing

Most of the research on alpine treeline shift has primarily been based on field data with a limited geographical extent. Due to its synoptic view and historical records for a wide area, remote sensing is an important tool to study alpine treeline and changes in the recent past. This study confirms that there is an upward shift of vegetation in the alpine zone of the Himalayas. The mean upward shift of the treeline is found to be of the order of 388 ± 80 m.

Alpine life zones are areas lying between the altitudinal treeline, or its substitutes, and the altitudinal limits of life, or the snow line. The alpine life zone is globally distributed, from polar to tropical latitudes, and occurs across oceanic and continental climates. Owing to the compression of thermal zones and isolation caused by low temperature, the alpine ecosystem usually shows high level of endemism and sensitivity to temperature change. Also, this area being among the most pristine environments on earth, least influenced by anthropogenic activities, provides an ideal 'natural laboratory' for climate impact research studies. The alpine treeline is the uppermost elevation where any individual tree having a height of 2 m or more can be found[1]. Usually a treeline is not a clear-cut line between forest and non-forest vegetation, but a transition zone (ecotone) from dominant trees to shrubs or grassland. The treeline species are at the threshold of their climatic limits. Factors related to tree growth or seed production and germination, such as temperature, precipitation, solar radiation, and wind or soil nutrient can inhibit the treeline from moving further towards higher latitudes or altitudes[2]. Any change in the climate, which perturbs the vegetation–climate equilibrium, will lead to significant changes in the demographic patterns of these species. Amongst these, temperature is the most common limiting factor affecting various aspects of vegetation dynamics[3].

Previous studies from the treeline zones show that the vegetation has fluctuated in the past in response to long-term climatic changes. Studies on the impact of ongoing warming under the background influence of greenhouse gases also show that during the past few decades plant species have shifted to higher elevations, and the shifting rate varies with species and largely depends on their sensitivity to climate. Strong evidence of climate-induced upward migration of alpine treeline has been reported from the Alps in Europe[4]. Studies carried out in Sweden have shown that at the border between the woods and bare mountains, trees that require warm temperatures, such as oak, elm, maple and black alder, have become established for the first time in 8000 years. Mountain fens are drying up, giving way to sedge and grass vegetation, and at the highest elevations, formerly the domain of sterile gravel and boulders, fens are found to occur. In the Nordic mountain, alongside the melting of glaciers, an upward shift in timberline (about 200 m) has been noticed[5]. Moreover, the birch forests are losing ground to spruce and pine, which are more competitive in a warmer and drier climate.

The studies so far conducted strongly indicate that the alpine world is evincing major changes despite the modest increase in temperature. Present prognoses of a temperature increase of 3°C by 2100 will entail considerably more sweeping changes. The knowledge generated by the current monitoring system is a precondition for models that predict the impact of a possibly warmer future. However, such observations for the Himalayan region are limited. Treeline in the Himalayan region varies from site to site depending on the position of the snow line. Its location in the western part of the Himalayas is at about 3600 m. It descends as low as 2550 m in Gilgit or is as high as 5000 m at Thalle La in the Karokoram ranges[6]. Tree-ring analysis of birch, a broadleaved tree in the central Himalayan treeline, showed correlation of increased tree growth with retreat of glaciers. Upward shift of pine in the Saram, Parabati Valley, Himachal Pradesh[7], and greening and recruitment of treeline in Nanda Devi Biosphere Reserve (NDBR)[8] Central Indian Himalayas based on a study of sapling recruitment pattern at higher altitude slopes have also been reported. All these random and isolated findings indicated the changing scenario of the Himalayan alpine life zone.

The treeline is a space- and time-related phenomenon. When assessing treeline sensitivity and its potential response to changing environmental conditions, spatial scale plays an important role[9]. The 'treeline', defined by a certain canopy coverage (e.g. 30% or 40%), can be mapped from satellite images or other remote sensing techniques[10]. The term 'line' is used as a convention, because, in reality, these occur in patches and never manifest as a continuous 'line'. What might be an obvious line from great distance offers a rather gradual, fragmented picture *in situ*. So the term 'line' does not imply a physical line, but rather refers to a boundary or obvious transition zone at the above level of precision. The minimum height for a tree should be 2–3 m at the treeline. However, in the context of remote sensing, this definition is subjective and refers to the transition of clear-cut tree zone to alpine vegetation zone. The alpine other vegetation line is the transition from any form of vegetation, including mosses, lichen to permanent snow line.

In remote sensing studies of vegetation, spectral vegetation indices are normally used. Among all vegetation indices, Normalized Difference Vegetation Index (NDVI) is widely used in detecting vegetation change, vegetation greenness and vegetation status, as it has good correlation with canopy cover and leaf area index[11]. Unlike the nominal land-use type in classified images, NDVI has the advantage of quantifying continuous changes to vegetation within each pixel, and it can distinguish between bare ground areas and partially vegetated areas, or between sparse and densely vegetated areas[12]. Remote sensing is now recognized as an essential tool for viewing, analysing and characterizing the alpine treeline ecotone[13]. Mapping of treeline, vegetation line and analysing shift in these using remote sensing data have been reported for a site in NDBR[14].

Based on the above observations, a study was taken up at the Space Applications Centre, Ahmedabad, to analyse the change in treeline and alpine vegetation line in the Indian Himalayan region. Here we highlight the results of remote sensing-based observations on treeline changes in Uttarakhand, India.

Uttarakhand has a geographic area of 53,483 sq. km (≈ 1.6% of the country). The state is situated in the northern part of India and shares international boundary with China in the north and Nepal in the east. It extends between lat. 28°43′N and 31°28′N and long. 77°34E′–81°03′E. About 64.79% of the state's geographic area comes under forests and about 19% is under permanent snow cover, glaciers and steep slopes where tree growth is not possible due to climatic and physical limitations. The altitude above 3000 m is generally considered as a zone of sub-alpine and alpine trees.

The study involves data selection, pre-processing, vegetation index calculation, thresholding based delineation and change analysis of treeline and other vegetation lines. Orthorectified IRS-P6 LISS-III images of 2006 (UTM/WSG84 projection) were used with path/row of 99/50, 98/50, 97/49, 98/49 and 96/49 and acquisition dates of 23 November, 31 December, 15 October, 31 December and 10 October respectively, to delineate the current status of treeline and vegetation line. Landsat MSS data of 1972–1976 were used with path/row of 157/38, 156/39, 156/38, 155/39 and 157/39 and acquisition dates of 12 January 1979, 19 November 1976, 26 October 1972, 6 December 1976 and 14 November 1972 respectively, as reference data for change analysis. Digital number values were converted to reflectance and an image-based atmospheric correction was used for data normalization. NDVI images were generated using these set of corrected and normalized datasets. Global Digital Elevation Model (GDEM) of ASTER was used to generate elevation contours.

Tree and other vegetation categories were made using a thresholding approach on NDVI data for the area above 3000 m elevation. The threshold NDVI values were arrived at by taking signatures from the known dense forest patches of sub-alpine forest (SAF) and those of alpine meadows. The treeline threshold was found to be >0.4, and the other vegetation lines fall in the 0.25–0.4 range. The respective NDVI thresholds were subjected to 'iso-NDVI-line' generation, based on bi-cubic spline interpolation algorithm. The isolines thus generated were subjected to groupings based on the threshold values and further classified as treeline and other vegetation lines based on the continuity of these classes. The smaller patches of the treeline and other vegetation lines were largely avoided to form isolines. Corrections for hill-shadow areas were carried out using visual editing. Validation of the results was done using field surveys.

Station points at every 30 m were generated on the treeline and other vegetation lines for past as well as current periods. The DEM values were extracted for each station point location. The change in alpine treeline ecotone (ATE) was studied as a function of shift in altitude from the past (1970s) to the current (2006) position. The shift locations were computed using GIS techniques. Equal numbers of station points generated over the past and current ATE were joined to form shift lines. The 'from' and 'to' nodes having elevational information extracted from DEM were subtracted to populate the shift values in the vector table. Surface length was also computed using DEM as a surface layer. GIS queries were made to locate the maximum shift zones to spot the direction and magnitude of the change.

To ascertain the overall uncertainty in the treeline shift, an analysis was carried out. Since both horizontal and vertical errors in DEM can lead to vertical errors in the results of the surface elevation changes of the treeline, mapping uncertainty of 100 m for LANDSAT and 50 m for LISS-III on the treeline was used to find out the effect on vertical errors. Vertical errors due to horizontal treeline mapping errors were taken into account in relation to each pixel slope (in degrees) on the treeline. The vertical error of DEM was combined with the vertical errors due to horizontal misalignment in both past and current treeline separately. This was achieved by calculating the quadratic sum of the errors. These errors were then used to calculate the overall uncertainty in alpine treeline shift.

The terrain analysis showed that around 15,244 sq. km area (29%) of the state falls in the elevation range of 3000 m and above. This region is spread over 6 districts and 42 Survey of India (SOI) topographic maps of 1 : 50,000 scale, which formed the spatial framework of mapping. Since 7 map sheets belonged to area under permafrost, only 35 map sheets having alpine ecotone features were of specific interest for this study. About 19% of Uttarakhand is devoid of vegetation, because of bioclimatic limitations and other factors responsible for the growth of plants. Total forested area above 3000 m comes to about 1801 sq. km. As one travels from the lower to higher altitudes within SAF, from 2000 m elevation onwards, the tree density reduces and composition of the trees also changes. Finally, it gives way to alpine meadows dominated by grasslands and herbaceous plants. At this ecotone, which is termed as the treeline, birch (*Betula utilis*), fir (*Abies pindrow*) and *Rhododendron* species exhibit dominance. The treeline species found in a site near Kedarnath are *Abies spectabilis*, *Betula utilis*, *Quercus semecarpifolia*, *Rhododendron campanulatum* and *Rhododendron arboreu.*

The area between the alpine treeline and other vegetation lines of Uttarakhand lies between 29°53′16″–31°18′42″N lat. and 78°8′34″–80°58′31″E long. The current treeline as derived using 2006 LISS-III data stretches about 2962 km surface distance. It is spread over six districts from Uttarkashi in the northwestern part to Pithoragarh in the northeastern part of the state. Chamoli District has the largest share of the treeline (30.62%), followed by Uttarkashi (29.12%). Around 98% of the treeline is in the elevation range 3000–4000 m (Table 1). The distribution of current treeline in relation to elevational ranges in different districts is shown in Table 2. The average elevation of the current treeline in the state is found to be 3542 m.

The treeline during the 1970s covered about 1650 km surface distance with average elevation of 3166 m. Thus, there is a mean upward shift of the treeline of the order of 388 ± 80 m. The difference in the surface distance from the past to the current period is mainly due to the zigzag nature of the ingression along suitable elevational gradients (Figure 1). The mean upward shift of the treeline was highest in Chamoli District (430 m) and lowest (360 m) in Uttarkashi and Bageshwar districts (Table 3). Magnitude

Table 1. Overall distribution of current treeline in relation to elevation range in Uttarakhand

Elevation zone (m)	Percentage of surface length of current treeline
< 3000	0.24
3000–4000	97.63
> 4000	2.13

of upward shift in terms of elevation range showed that at many places in the Chamoli District, the upward shift of the treeline crossed 1000 m, which is significant (Table 4). However, it is interesting to note that the site belonging to the highest elevation, where the current treeline goes, does not show any change. This site is located at 4573 m and about 7 km from Gangotri town towards the NE direction in Uttarkashi District (79.00°E long. and 31.02°N lat.), falling in the SOI map sheet no. 53M/4. The same site also belongs to the highest treeline position during the 1970s period.

Analysis of field data for a site in Bedini Bugyal was done on change dynamics and species composition. Bedini Bugyal is the Himalayan alpine meadow, Chamoli District and falls within the protected Nanda Devi Biosphere Reserve area. The treeline in this area goes up to 4120 m asl. Maximum shift of treeline in this region was observed to be around 600 m (Figure 2 *a*). Field visit showed that the treeline of this area is mostly composed of fir–birch up to 3500 m and birch–rhododendron up to 4120 m. Alpine pastures are found at 4425 m in the southern aspect of the hills, whereas pastures are found below 3000 m in the northern aspects. Newly planted saplings of 7–8 years are mainly those of *A. pindrow* and *R. campanulatum* observed in the northern slopes, confirming the upward shift of tree species (Figure 2 *b*).

The vegetation line encompasses all areas above the elevation range of the treeline having the signature of vegetation. This included great expanses of pure meadows (grasslands), flowering herbs and scattered miscellaneous vegetation. The vegetation near the snow line and in the proximity of the glaciers was rather thin, scattered, apart from the mosses and lichens. While the former are well identified using the NDVI threshold, the latter have poor accuracy and overlap with scree. Thus, the vegetation line identified includes only well-developed vegetation areas.

Table 2. Distribution of current treeline in relation to elevation range in different districts of Uttarakhand

District	< 3000 m	3000–4000 m	> 4000 m
Bageshwar	0.04	99.85	0.11
Chamoli	0.42	98.91	0.67
Pithoragarh	0.50	99.15	0.35
Rudraprayag	0.00	100.00	0.00
Tehri Garhwal	0.00	100.00	0.00
Uttarkashi	0.00	93.72	6.28

The current other vegetation lines cover about 5274 km surface distance. The average elevation of this line is 4158 m with maximum elevation of 6157 m. During 1972, the other vegetation lines covered about 2010 km surface distance with an average elevation of 3447 m. Thus, there is about 700 m upward shift in case of other alpine vegetation lines.

Previous studies from the treeline zones in the Himalayas had shown that the vegetation has fluctuated in the past in response to long-term climatic changes. Studies on the impact of ongoing warming under the background influence of greenhouse gases world over have shown that during the past few decades alpine plant species have shifted to higher elevation, though the shifting rate varies with species and their sensitivity to climate. This study confirms that there is an upward shift of vegetation in the alpine zone of the Himalayas. Though there may be some error in the exact elevation gradient in general, there is no doubt that the change is significant. However, any meaningful research to model the vegetation

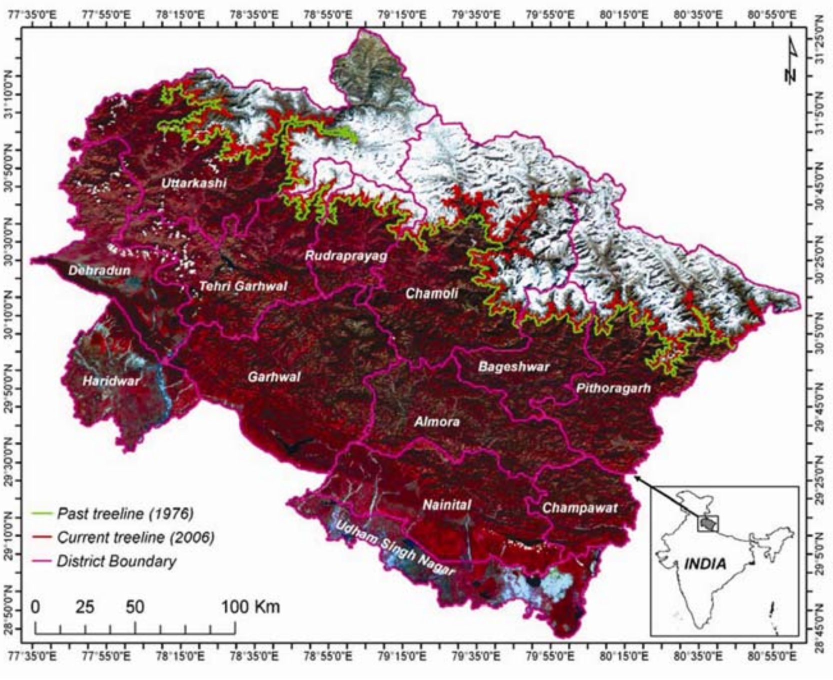

Figure 1. Map showing the status of alpine treeline in 1972 and 2006 in the state of Uttarakhand (overlaid on false colour composite of IRS-P6, LISS-III, year 2006).

Table 3. Mean upward shift of treeline in different districts of Uttarakhand as observed from 1970 to 2006

District	Mean shift (m)
Uttarkashi	360
Tehri Garhwal	400
Rudraprayag	390
Chamoli	430
Bageshwar	360
Pithoragarh	390

Table 4. Percentage of upward shift of treeline under different elevational shift ranges in Chamoli District, Uttarakhand

Elevation shift class (m)	Percentage of samples
0–200	23.89
201–400	33.60
401–600	20.24
601–800	10.73
801–1000	4.86
1000–1600	6.68

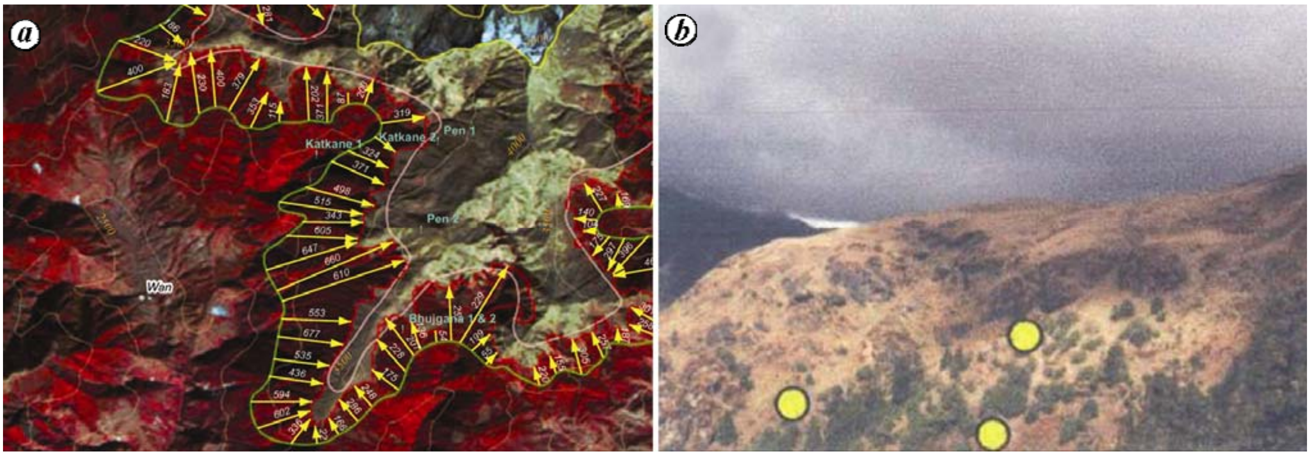

Figure 2. ***a***, Treeline change analysis in Bedini Bugyal area. The arrows show the change in direction and magnitude. ***b***, Field photograph showing ingression of *Abies pindrow* on north-facing slopes in Bedini Bugyal area (encircled area are ground sample locations).

dynamics response to warming requires an effective, long-term ground-observation strategy. Thus, a programmatic imitative is the need of the hour in line with the GLORIA (Global Observation Research Initiative in Alpine environments) network. To plan for such work, satellite remote sensing data are the best option in view of the rugged, inaccessible and vast stretch of the Himalayan alpine area. This study has shown the potential of remote sensing data to create and update a database of alpine treeline and vegetation lines. High-resolution DEM from Indian Cartosat along with high-resolution multispectral LISS-IV data can be then used to select multi-summit sites for field data collection on species diversity for long-term monitoring.

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