ALPINE TREELINE ECOTONE DYNAMICS AND GREENING TREND IN EASTERN HIMALAYA THROUGH REMOTE SENSING TECHNIQUES

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ABSTRACT: Global warming is inducing the treeline ecotones to migrate to higher elevations in the Himalaya. Satellite remote sensing of alpine treeline ecotone in eastern Himalaya reveals an upward shift in four decades. The past alpine treeline ecotone has phenological changes and greening trend. In this study, satellite-derived NDVI data from Landsat-2 (MSS), Resourcesat-2 (LISS-III) and NOAA-AVHRR is used to investigate the long-term dynamics at the treeline ecotone. It is observed that the treeline has shifted *c*. 452 ± 74 m upward in four decades. The vertical rate of treeline shift is found to be *c*. 113 m decade^{-1}. Phenology has changed significantly from the year 1982 to 2015 (34 years). The time series data of GIMMS-NDVI from NOAA-AVHRR confirms the increase in the length of the season and greening trend at the treeline. The average start of the growing season (SOS), the length of the growing season (LOS) and the end of the growing season (EOS) have advanced in the past treeline ecotone of 1974. We used mean monthly surface air temperature and precipitation to correlate with the phenological and greening trend. The alpine treeline ecotone upward shift, phenological changes and greening is expected in such warming scenarios. This study confirms that there is a significant upward shift of alpine treeline ecotone in eastern Himalaya with lengthening of growing season and greening over alpine treeline ecotone.

1. INTRODUCTION

Climatic variability is changing the biome distribution in the Himalaya at a rapid rate than other parts of the globe (Field et al., 2014). Alpine treeline ecotone (ATE) is an imaginary line connecting the uppermost or most northern patches of short stature trees (*krummholz*) (Körner, 2012). Upward movement of the treeline is a fingerprint of climate change. The treeline is having an upward shift to a higher elevation, suggesting climate change (Grabherr et al., 1994). Temperature is the most important factor that governs the growth of treeline (Mayor et al., 2017). Movement of the treeline to a higher elevation will cause the extinction of the alpine species mostly dominated by herbs and shrubs. The tree species will compete for the available resources and as a result, the herb and shrub species will get extinction due unavailability of space in the summits. To observe this changes in the treeline at the landscape-level, multi-temporal satellite data is most important.

In Himalaya, the treeline is shifting upward to higher elevation because of global warming (Mohapatra, 2015; Schickhoff et al., 2015; Singh et al., 2012). One of the dominant treeline species, *Betula utilis* D. Don has shifted to higher elevation and will continue to move to higher elevation in future also (Bobrowski et al., 2017; Singh et al., 2013). Trees have comparatively higher growth physiology than the herb and shrubs dominated alpine. Higher growth physiology indicates higher photosynthesis or more reflectance of near-infrared light by the plants. This near-infrared light is detected in Normalized Difference Vegetation Index (NDVI). Changes in the vegetation phenology and greening is an indicator of climate change in the treeline zone. Increase in temperature increases the length of the growing season of vegetation (Xu et al., 2013). In the Greater Hindu-Kush Himalaya, mean air temperature has increased at the rate of 0.06 °C yr^{-1} causing advancement of the start of the growing season (SOS) and length of the growing season (Shrestha et al., 2012).

Inaccessibility and remoteness of the ATE in Himalaya make remote sensing an attractive method for studying and conducting research. Resourcesat-2 and Landsat-2 imagery provide multispectral data at a medium resolution which enables the large-scale study of ATE. The Resourcesat-2 Linear Imaging Self Scanning sensor (LISS-III) with a spatial resolution of 23.5 m is useful for delineating ATE at current period. The Landsat-2 Multispectral Scanner (MSS) with a spatial resolution of 60 m provides long-term historical data from 1972, is useful for studying the impact of climate change on ATE. In this paper, a semi-autonomic method of treeline delineation at the landscape-level has been done using geographical information system (GIS) and validated from field surveys.

2. MATERIALS AND METHODS

2.1 Study Area

The study area is the mountainous eastern Indian Himalayan region of Arunachal Pradesh. The total geographical area is 83,743 km^2 with 80.3 % of forest cover (SFR, 2015). The forest cover includes 20,804 km^2 of very dense forest, 31,301 km^2 medium dense forest and 15,143 km^2 of open forest cover. As per the digital elevation model, the highest elevation reaches up to 7337 m a.m.s.l and slopes vary from 0º to 89º. The large biodiversity and availability of many endemic species make it one of the hot spots of biodiversity in eastern Himalaya. The total annual rainfall in the year 2014 is 2403.2 mm (Kaur and Purohit, 2016). High precipitation in both the winter and summer makes the alpine forest most luxuriant in eastern Himalaya. The field study was done in three summits of Tawang (highest summit point 1(HSP1): 27º 37' 19.6" N, 91º 51' 43.1" E, 3657 m; HSP2: 27º 38' 17.8" N, 91º 51' 29.4" E, 3953 m; HSP3: 27º 39' 41.1" N, 91º 51' 25.8" E, 4179 m). It is established as one of the target sites for long-term monitoring of alpine ecosystem under Himalayan Alpine Dynamics Research Initiative (HIMADRI) (Singh, 2015). The most dominant treelines species are *Rhododendron* L. (includes *R. glaucophyllum* Rehder, *R. setosum* D. Don, *R. flinckii* Davidian, *R. hodgsonii* Hook. f., *R. thomsonii* Hook. f., *R. wightii* J. D. Hooker and *R. campanulatum* D. Don), *Juniperus indica* Bertol, *J. recurva* Buch.-Ham. ex D. Don and *Abies densa* Griff. The other dominant alpine species are *Persicaria hydropiper* (L.) Delabre, *Selaginella* P. Beauv., *Berberis* L., *Rhizocarpon* Ramond ex DC., *Cyperus* L., *Swertia hookeri* C. B. Clarke, *Fragaria nubicola* Lindl. ex Lacaita, and lichens.

2.2 Data

Resourcesat-2 LISS-III (spatial resolution: 23.5 m) and Landsat MSS (spatial resolution: 60 m) imagery are used for delineation of alpine treeline ecotones for current and the past, respectively. The digital elevation model of orthorectified Cartosat-1 (CartoDEM) at a spatial resolution of 10 m is used for elevation. The GIMMS NDVI3g datasets from 1982 to 2015 are used to study the phenology and greening trends of alpine treeline ecotones. The GIMMS3g NDVI data is a long-term dataset derived from Advanced Very High-Resolution Radiometer (AVHRR) sensors aboard the National Oceanographic and Atmospheric Administration (NOAA) satellites 7, 9, 11, 14, 16 and 17 (Pinzon and Tucker, 2014). It has a spatial resolution of 8 × 8 km and a temporal resolution of 15-days. Ground truth information for validation of delineated treeline is done from field studies and literature.

2.3 Methodology

2.3.1 Delineation of Alpine Treeline Ecotone

Orthorectified, terrain corrected and cloud-free Resourcesat-2 LISS-III imagery of 2014 (UTM WGS84 projection) for current and orthorectified Landsat MSS imagery of 1974 for the past is used to delineate alpine treeline ecotone. Resourcesat-2 LISS-III multispectral image is atmospherically corrected using the Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercube (Matthew et al., 2000). Atmospheric correction of Landsat MSS image is performed using Dark Object Subtraction method (Chavez, 1988). Vegetation indices derived from different sensors are sensitive to the difference in their bandwidth and viewing geometry. These vegetation indices should be normalised for valid comparison between them. The Landsat MSS NDVI is normalised w.r.t. Resoursesat-2 LISS-III NDVI using the equation developed by Steven et al. (2003) (see equation (1)).

$$NDVI_{RS2} = -0.020 + 1.065 \times NDVI_{LandsatMSS} \quad (1)$$

Further normalisation is also carried out using linear regression model of pseudo-invariant features (Anderson et al., 2011). The past (1974) and the current (2014) treeline delineation has been done using automatic contour delineation method in ArcGIS (ESRI 2016). The field survey of alpine treeline locations and other ancillary data (digital forest map of SFR, 2015) are used for ascertaining the NDVI value (0.45) over the alpine treeline ecotone. The treeline is delineated by connecting iso-NDVI-line based on bi-cubic spline interpolation and filtering small spurious contours automatically generated on the defined threshold. The hill shadow in the terrain and other errors is manually corrected. Station points at 10 m intervals are generated for both the past and current treeline ecotone. The elevation values for each station point (in meters) is extracted from Cartosat-1 DEM. Different sets of satellite data and products have been used for delineating the treeline positions and their elevation. Therefore, the estimates are subjected to inherent errors associated with each step of the process and datasets used. Vertical elevation errors due to planimetric treeline mapping are taken into account in relation to each pixel slope (degrees) on the treeline. The errors due to planimetric misalignment are combined with the elevational error of DEM for both the past and current treeline separately. It is achieved by calculating the quadratic sum of the errors which are used for estimating the overall uncertainty in treeline shift.

2.3.2 Extraction of Phenological Parameters and Trend Analysis

The phenological trend for the past treeline ecotone is studied using 15-days NDVI time series. The phenological matrices are extracted from 1982 to 2015 (34 years). The '*greenbrown*' package (Forkel et al., 2013; 2015) in R statistical language (R core Team, 2017) is used to estimate the phenological parameters and greening trends. The permanent gaps which usually observed in the winter months are filled in each time series data. The smoothed and daily interpolated time series of NDVI is used to estimate the SOS and EOS for each year. The inflexion point 0.5 is set for retrieving the SOS and EOS (White et al., 1977). SOS and EOS estimation at lower NDVI values are erroneous because these values are affected by snow cover dynamics and cloud contamination. The LOS is estimated as the difference between EOS and SOS. The peak and trough of the curve are considered as the maximum and minimum greenness of that year, respectively. The trends in the yearly phenological parameters and greening are computed based on linear least square regression.

3. RESULTS AND DISCUSSION

3.1 Upward Shift of the Alpine Treeline Ecotone

In the past four decades, there are significant changes in the alpine treeline ecotone elevation. There is an upward shift in the alpine treeline ecotone elevation from the year 1974 to 2014 (Figure 1). Comparing both the past and present mean elevation status of the treeline, it is observed that the mean upward shift in the treeline is 452 ± 74 m i.e., *c*. 113 m decade^{-1}. In 1974, the mean elevation of the treeline is *c*. 3684 m a.m.s.l., whereas in 2014 i.e., after four decades, the treeline has shifted to *c*. 4136 m elevation in the eastern Himalaya. The maximum elevation of the past treeline is 5240 m, which has shifted upward to an altitude of 5679 m in four decades. The positions and the upward shift of the treeline vary throughout the Himalayan mountains. This is because of various factors responsible for treeline to be formed like topography, macro- and microclimatic, and ecological conditions responsible for the survival of treeline species.

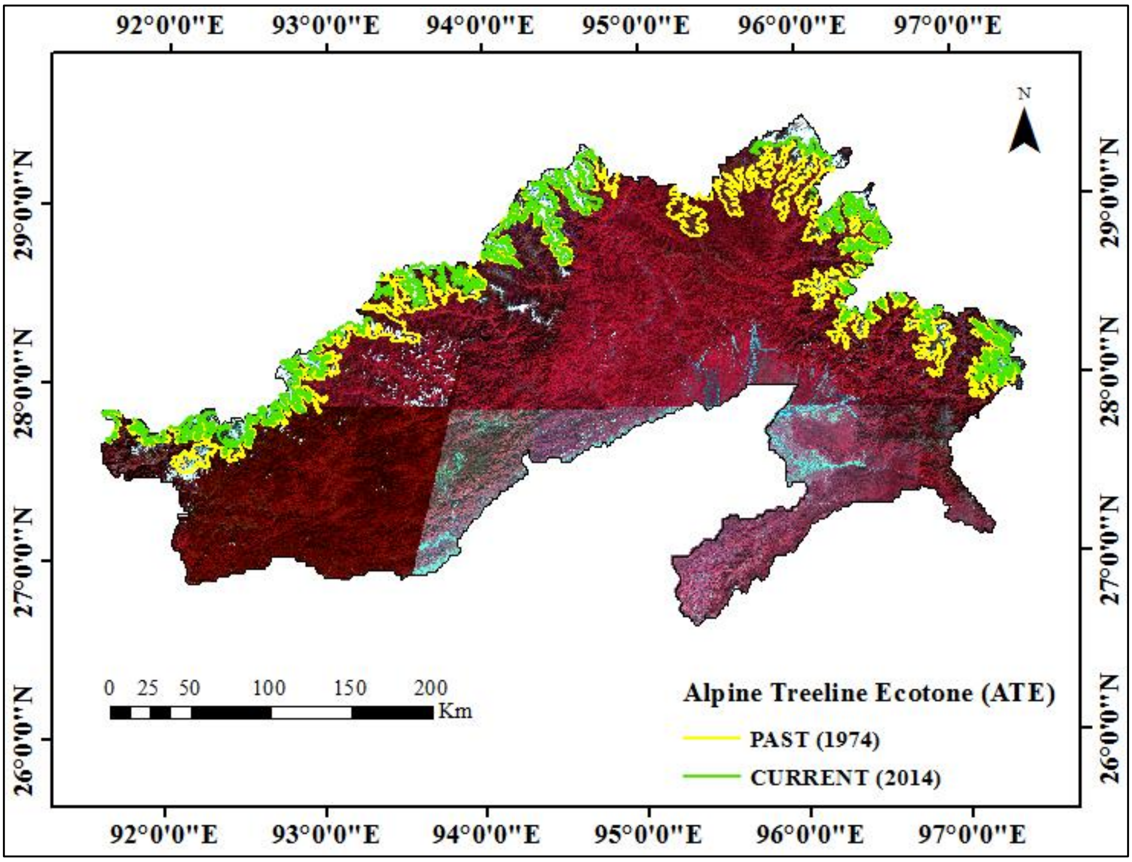

Figure 1. The past and the current alpine treeline ecotone draped over false colour composite (FCC) of Resourcesat-2 (LISS-III).

The presence of the treeline surveyed during September to October 2014 and the presence data from global biodiversity facility (GBIF) in eastern Himalaya matches well with the satellite observed treeline elevation (Table 1). *Rhododendron* L. is the most dominant treeline species that is found in the alpine treeline ecotone in the eastern Himalaya.

Table 1. Locations of the treeline species and their elevation.

Treeline species	Latitude (°N)	Longitude (°E)	Elevation (m)
Rhododendron L.	28.35	96.61	3810
Rhododendron L.	28.33	96.62	3810
Rhododendron L.	27.80	96.90	4119
R. crinigerum Franch.	27.80	96.90	4119
R. sidereum I. B. Balf.	27.80	96.90	4119
R. ramsdenianum Cowan	27.80	96.90	4119
R. arizelum I. B. Balf. & Forrest	27.80	96.90	4119
R. pudorosum Cowan	27.70	92.20	4375

The treeline ecotone dominated with pines in Himachal Pradesh Himalaya has an upward shift of 19 m and 14 m decade^{-1} in south and north slope, respectively from the year 1860 to 2000 (Dubey et al., 2003). In one of the previous study on ATE in western Himalaya by remote sensing (Singh et al., 2011; 2012), the upward shift of ATE is 110 m decade^{-1}. The current study (the year 1974 to 2014) shows a higher rate of upward shift of treeline in the eastern Himalaya. This is because of the more humid conditions in the eastern Himalaya compared to that of western Himalaya (Dutta et al., 2013). This upward shift of treeline ecotone can be regarded as significant changes in the alpine ecosystem caused by climate change with global warming. The shift that has been observed at the landscape-level has a higher shift in the treeline that the field-based observations.

3.2 Phenology and Greening Trend in Alpine Treeline Ecotone

Patterns of phenology and greenness have changed remarkably in 34 days. There is an increase in the length of the growing season at the rate of 3.3 days decade^{-1}. It ranges from 134 to 193 days (Figure 2a) in the three decades. The LOS in the year 1982 was lowest i.e., 134 days, whereas, in the year 2015, it is 162 days. The start of the growing season is starting early at the rate 0.7 day decade^{-1}. The SOS range from 216 (4th August) to 263 (20th September) Julian day. The end of the growing season is late at the rate of 0.5 day decade^{-1}. The EOS range from 34 (3rd February) to 79 (19th March) Julian day.

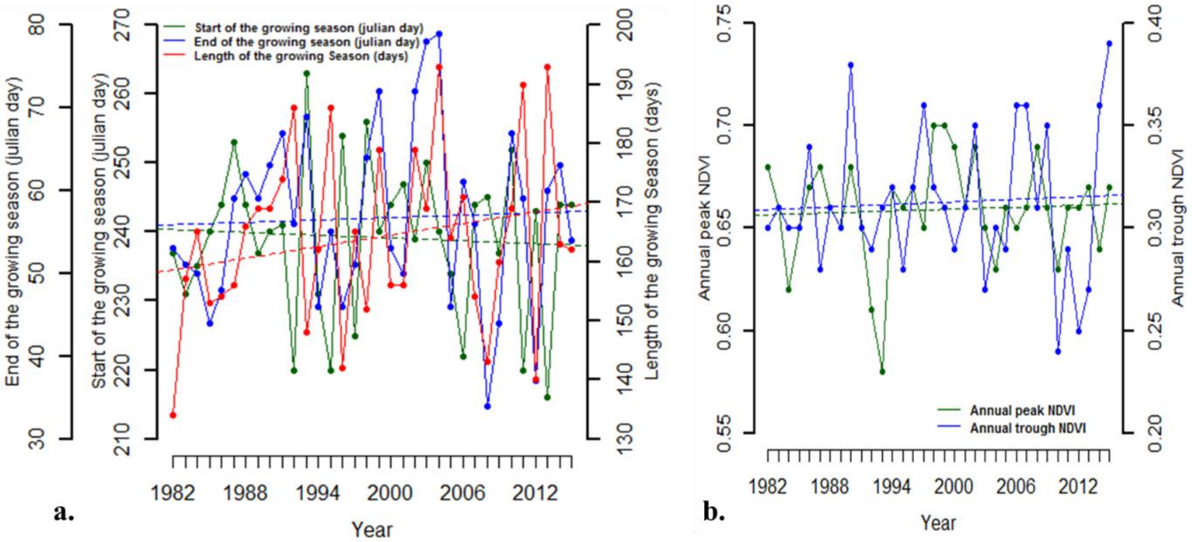

Figure 2. a) Phenological changes in the past alpine treeline ecotone. b) Greening trend in the past treeline ecotone.

The start of the growing season for alpine ecosystem begins after snow melting followed by an increase in the soil moisture content (Reed et al., 2003). After the monsoon in the month of July, August, and September, the alpine treeline species get enough soil moisture for their growth causing leaves flushing and the growing season starts. Peak growing season NDVI is a proxy for net primary productivity (Burrell et al., 2017). There is a positive trend in the annual peak NDVI in the past four decades. The annual trough or base value has also increased in the past ATE which signifies an increase in the non-green or standing biomass of the ATE (Figure 2b). The annual peak NDVI values range from 0.58 to 0.69. The annual trough NDVI values range from 0.24 to 0.39. The peak and trough have increased at a rate of *c*. 0.002 NDVI decade^{-1}. The past alpine treeline ecotone is getting greener in response to high-altitude warming.

4. CONCLUSIONS

The alpine treeline ecotone upward shift, phenological changes and greening is expected in such warming scenarios. This study confirms that there is a significant upward shift of alpine treeline ecotone in eastern Himalaya with lengthening of the growing season and greening over alpine treeline ecotone. The past treeline ecotone has got greener and stays green for a longer period of time than it was before four decades. During 1974, the mean elevation of ATE is *c.* 3684 m a.m.s.l. The current mean elevation of ATE is 4136 m a.m.s.l. which is validated from field observations. The upward shift of ATE in the eastern Himalaya is *c.* 452 ± 74 m upward in four decades i.e., *c.* 113 m decade^{-1}. This cause the extinction of the other lower plant groups dwelling above the treeline in the alpine region because of lack of space at the peak of summits. Increase in the length of the growing season (3.3 days decade^{-1}), early start of the growing season (0.7 day decade^{-1}) and late end of the growing season (0.5 day decade^{-1}) further confirms the upward shift of the treeline ecotone. The increase in the annual peak of NDVI suggests an increase in the productivity in the past ATE. The increase in the trough value indicates an increase in the standing biomass. All these observed changes are the fingerprints of climate change in the alpine ecosystem of high altitude Himalayan mountains.

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