Phenological variability and greening trend at alpine treeline ecotone (ATE)
1. Introduction

Phenological changes in vegetations are another most important phenomenon which is linked to changes in weather pattern in short term and climate change in long term. Since, phenological events are controlled by environmental and climatic factors, therefore considered as a sensitive biosphere indicator of climate change (Chambers, 2009). Phenology in this chapter is restricted to foliar phenology which is about the study of recurrent phenomena of leaves (e.g. new leaf initiation, maximum leaf period, and leaf fall or senescence). Vegetative phenology provides detailed information on seasonality and cycle of leaf functioning and is vital for understanding the interactions between the biosphere and the climate (Arora & Boer, 2005). Phenological pattern studies through NDVI helps in understanding dynamics of vegetation with regards to carbon sequestration and earth-atmosphere energy interaction. Time series vegetation indices can also help in recognizing phenological events like leaf initiation, leaf colouring, and leaf fall (Agrawal et al., 2003). The timing of these events are often closely related to temperature and the amount and timing of precipitation. In temperate zones an increase in temperature leads to an earlier start of the growing season and a may be a later end. The length of the growing season is expected to increase with warming (Myneni et al., 1997a). Only in those places where environmental conditions like drought, flooding or snowfall limit plant growth will an increase in temperature not immediately result in a lengthening of the growing season. Plants are flexible in adjusting the timing of their phenological events to changes in climate conditions. Increasing density of treeline trees at ATE indicating a greening trend in time series satellite data can also be an indicator of changes in the ecology of treelines, which may precede any detectable movement of ecotone in remotely sensed images. Most forests in treeline areas are sparse, with low canopy coverage. A greater growth response (i.e. grew denser) in treeline forests compared to reference treeline forests makes it possible to get detected using remote sensing techniques. Net primary productivity at alpine treeline is also expected to increase in response to global warming.
2. Phenological variability:

Understanding the changes in phenology is necessary to infer the response of plants towards climatic variation. Meteorological and other parameters such as temperature, rainfall, day-length, relative humidity and soil moisture are regulating the vegetative phenology. Extraction of phenological variables such as start of the season (SOS), maximum of season (MOS), end of the season (EOS), and length of the season (LOS) are important elements for such studies (fig.8.1). These phenological variables are generally measured in filed at regular interval for few key tree species but with the availability of time series data from space borne satellites it can be measured at landscape level.

Normalized difference vegetation index (NDVI) is a normalized ratio of red and near infra-red (NIR) spectral reflectance (equation.4.7) presenting the degree of absorption by chlorophyll in Red wavelength (proportional to leaf chlorophyll concentration) to the degree of reflectance in NIR wavelength (proportional to green leaf density) (Tucker, 1979). In this study, SPOT-VGT NDVI 10 day composite product with 1 Km X 1 Km spatial resolution has been used for 10 years (1999 to 2008). The climatic data such as maximum temperature, minimum temperature, mean temperature, and rainfall were obtained from Indian Meteorological department (IMD) in the form of 1° X 1° gridded spatial images for temperature (Rajeevan et al., 2006, Srivastava et al., 2008) and 0.25°x0.25° gridded rainfall (Pai et al., 2014). The data was downloaded and read for the ATE coordinates using MATLAB code developed for this study (Appendix-II).

Deriving phenological parameters involves the data smoothening, filtering and curve fittings. SPOT VGT-NDVI product of 10 years (1999-2008) amounting to 360 bands (36 bands / year) - were loaded in TIMESAT ver. 3.02 (Jönsson & Eklundh, 2004) to get the smoothened NDVI profile at ATE locations. TIMESAT implements an adaptive Savitzky–Golay filtering method based on least-squares fits to the upper envelope of the NDVI data. This method uses local polynomial functions in the fitting. This methods uses a preliminary definition of the seasonality (uni-modal or bi-modal) along with approximate timings of the growing seasons. The seasonality in the
program is determined using data values \((t_i, l_i), i = 1, 2, \ldots, N\) for three years by fitting a model function (equation 8.1):

\[
f(t) = c_1 + c_2 \sin(\omega t) + c_3 \cos(\omega t) + c_4 \sin(2\omega t) + c_4 \cos(2\omega t), \quad \text{...............}(8.1)
\]

Where, \(\omega = \frac{6\pi}{N}\)

The first three basis functions determine base level and inter annual trend whereas the three pairs of sine and cosine functions correspond to, respectively, one, two and three annual vegetation seasons. The fitting procedure always gives three primary maxima. In addition, secondary and tertiary maxima may be found. If the amplitude of the secondary maxima exceeds a certain fraction of the amplitude of the primary maxima we have two annual seasons. For cases where the amplitude of the secondary maxima is low, the number of annual seasons is set to one.

The pre-processing to remove the spikes and outliers was carried out by applying a median filter. Further, adaptive Savitzky-Golay filtering and curve fitting was used to deduce the phenological parameters. This method fit a quadratic polynomial \(f(t) = c_1 + c_2 t + c_3 t^2\) for each data value \(y_i, i = 1, 2, \ldots, N\) to all \(2n+1\) points in the moving window and replace the value \(y_i\) with the value of the polynomial at position \(t_i\) in the equation 8.2:

\[
\sum_{j=-n}^{n} c_j y_{i+j} \quad \text{.................................(8.2)}
\]

To account for the negatively biased noise, the fitting is done in multiple steps. The result is a smoothed curve adapted to the upper envelope of the values in the time-series. The width, \(n\), (i.e. window size) of the moving window determines the degree of smoothing, but it also affects the ability to follow a rapid change. In TIMESAT the width \(n\) can be set by the user because, sometimes it is necessary to locally tighten the window. The adaption strength value (i.e. weights) can be provided in TIMESAT for setting the upper envelop. The phenological parameters (dates determined by the curve fitting) are not affected by these weights; however, the absolute NDVI value increases. To arrive at the window size for curve filtering,
number of envelope iterations and adaption strength value, a set of experiments were carried out based on the known phenology prevailing in the study area.

Seasonal data were extracted for each location. From the 10 years data, 9 seasons (n-1) were extracted. The start and end of foliage season can be set from 0-1. By trial and error method and from literature (Jönsson & Eklundh, 2002) the value of 0.1 i.e. 10% of the distance from the left and right minimum values from the maximum value of the curve was set. Peak of the curve (100%) has been considered as maximum greenness of that season. Maximum leaf fall rate was set to 0.5 i.e. 50% (inflection point) between the peak value and right side maximum value (fig. 8.1). Window size for curve fitting was determined as 17. Number of envelop iterations was set to 3 and the adaption strength was set at 5. The seasonality was found distinctly uni-modal in nature for the forest around ATE. From the curve fitting, the seasonality parameters were extracted and the composite dates were converted into the normal dates (Julian days) for each pixel. The timings of seasons do not normally follow the calendar year. For example a vegetation season may start in August, peak
in December, and fall off in April of the next year. Therefore, the time window selection was carried out accordingly. The extraction of images is done using the TSF_seas2img, a FORTRAN program which is an in-build algorithm provided in the TIMESAT. The zonal statistical analysis was carried out using these phenological images over the current ATE line. The mean phenological value from SOS, EOS and LOS images were extracted in GIS domain for each pixel falling on the ATE vector line.

In the study area, a rise in temperature, with availability of soil water from first week of April continues up to June. The pre-monsoon period is May and June and the snow starts melting in March to April. Because of the early availability of moisture, a majority of the species at alpine sites initiate growth and do not wait for the onset of the monsoon. The factor that decides growth initiation is snowmelt, which not only supplies soil water but also indicates a rise in temperature. At higher elevation, temperature is the most important factor in different phenological stages. Growth period lasts only 5-7 months because this area is completely covered by snow from January to April. If a species is commencing growth before 31 May, it is considered as early growing species. If growth commenced after 31 May, the species is considered to be a late growing species. Early growing species growth initiates from last week of April or in May. Late growing species growth begins in June or early July. Senescence at the community level is gradual from July to early September, after which it’s sudden and massive from the beginning of October due to heavy frosting and snowfall. Senescence is reported in all alpine plants during November and December due to heavy frosting and occasional snowfall (Nautiyal et al., 2001). The major tree/woody species showing such phenological patterns are Acer caesium Wall. Ex Brand., Betula utilis D. Don, Abies spectabilis (D.Don) Mirbel, Quercus floribunda Lind. ex Rehder, Quercus semecarpifolia Smith and Rhododendron campanulatum D.Don, while the major herbs are Frageria nubicola Lind., Potentilla astrosanguinea Ledd., Primula denticulata Sm., Tanacetum dolichophyllum (Kitam.) Kitam., Taraxacum officinale Weber and Viola biflora L. (Bisht et al., 2014).

Figure.8.2 shows scaled Savitzky-Golay filtered NDVI data over a past treeline to current treeline transition zone in Gangotri area. This clearly indicates that, the
area is dominated by a one seasonal (uni-modal) cycle. The beginnings and ends of seasons were located fairly close to each other in all the years. Near the treeline the season starts in May and ends in November with peak period in August (NDVI: 0.33 – 0.43). The variability in the seasonality parameters can be explained by meteorological data. Moisture availability is unlikely to be much significant constraint on plant growth as the district normal precipitation ranges from 10.7mm in October to 455.4mm in August with rainy days varying from 1 to 19 in October and August, respectively. It was found that, the starting date of the season fluctuates with the changing temperature in the treeline area. The increase in mean minimum temperature starts the greening season early and has bearing on the length of growing season with correlation coefficient of 0.66 (fig.8.3(b)). Initially, the start of the season is not in accordance with the general trend (fig.8.3(a)), may be due to increasing winter precipitation on the starting date of the growing season. In fact, in evergreen forests there is no distinct leafless period because of the phenomenon of “leaf exchange”; i.e. shedding of old leaves (during early dry season) is accompanied or immediately followed by bud burst and expansion of new leaves. The seasonality of the vegetation in this area, however, is well developed and can be explained with meteorological variables.

Figure 8.2. Scaled NDVI values for 10 years (1999 – 2008) from SPOT-VGT over treeline (Mean Altitude 3282m) in Gangotri. Time is in 10 day steps. [NDVI = scaled value *0.004)-0.1]
3. Greening trend

3.1 Changes in NDVI at past and current ATE of Uttarakhand

The NDVI in year 1976 as derived using Landsat (1970s) data (table.4.2) and new series of Resourcesat-1/2 of year 2012 & 2014 (table.4.3) is used for studying the changes in NDVI at past (year 1970s) and current ATE (year 2006). The mean difference in roughly 4 decades (1970s to 2014) at current ATE distributed at various elevation ranges are shown in table.8.1. The NDVI ranges from 0-1 however at ATE it remains below 0.6 in year 2014 and it remained below 0.4 around 38 years ago at the elevation range of 3,001 – 3,200 m amsl. The mean difference along decreasing elevation from 4,400 m to 2,800 m shows an increasing trend (table.8.1, fig.8.4) with...
R² of 0.95 and standard error of 0.02, which indicates that there has been densification happening at the attitudinally lower zones below ATE in past 38 years. Similar trend was also observed at the past ATE with R² 0.684 and lesser magnitude as compared to current ATE greening, suggesting that the past treeline has already reached to saturation in the greening trend.

### Table 8.1: Mean and difference of mean NDVI at current ATE (year 2006) and change from year 1976 to year 2014 with respect to elevation ranges

<table>
<thead>
<tr>
<th>Elevation Range (m) amsl</th>
<th>Mean NDVI_1976 at ATE</th>
<th>Mean NDVI_2014 at ATE</th>
<th>Mean NDVI Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2800 - 3000</td>
<td>0.245</td>
<td>0.476</td>
<td>0.232</td>
</tr>
<tr>
<td>3001 - 3200</td>
<td>0.322</td>
<td>0.525</td>
<td>0.203</td>
</tr>
<tr>
<td>3201 - 3400</td>
<td>0.317</td>
<td>0.498</td>
<td>0.181</td>
</tr>
<tr>
<td>3401 - 3600</td>
<td>0.294</td>
<td>0.463</td>
<td>0.169</td>
</tr>
<tr>
<td>3601 - 3800</td>
<td>0.273</td>
<td>0.397</td>
<td>0.124</td>
</tr>
<tr>
<td>3801 - 4000</td>
<td>0.239</td>
<td>0.334</td>
<td>0.095</td>
</tr>
<tr>
<td>4001 - 4200</td>
<td>0.235</td>
<td>0.244</td>
<td>0.009</td>
</tr>
<tr>
<td>4201 - 4400</td>
<td>0.232</td>
<td>0.239</td>
<td>0.007</td>
</tr>
<tr>
<td>Overall Mean</td>
<td>0.269</td>
<td>0.397</td>
<td>0.128</td>
</tr>
</tbody>
</table>

Figure 8.4. Graph showing mean NDVI difference (1970s to 2014) at different elevation over Current ATE in Uttarakhand

\[ y = -0.0002x + 0.736 \]

\[ R^2 = 0.949 \]
3.2 Densification and greening in ATE of Gangotri catchment

The treeline in Gangotri region of Uttarakhand is confined between 30°55′32.3″ N – 31°01′ 36″ N (lat.) and 78°56′6.5″ E – 79°06′ 24.5″ E (long.). The digital comparison of the treeline between year 1976 and 2006 found that all forested cells along the past treeline ecotone were still forested in 2006 with same or increased NDVI at certain places while certain non forested pixels in 1976 were converted to forest in 2006. The mean fAPAR data showed the greening trend (fig.8.5) at the treeline transition zone. A significant positive trend in mean fAPAR in 20 years has been observed. The slope was 0.004 per year. Ring-width chronology of *Pinus wallichiana* (AD 1650–1999) in Gangotri (Singh & Yadav, 2000) also confirms that there has been rapid greening especially in past three to four decades. SPOT-VGT based results indicated that during growing season (May-Nov) along rising elevation the greening trend is slowly diminishing. It was also found that near past and current treeline as well as near past vegetation line there is a greening trend. The points studied near current vegetation line do not show significant greening trend. Each sample point gained an average of 0.10 (standard deviation, σ 0.03) of NDVI in 10 years (fig.8.6). However, Landsat-MSS and IRS-LISS-III NDVI change in 30 years has been 0.10 to 0.20 (σ 0.06).

Relative to NDVI in each point, the σ was smaller in higher altitudes, suggesting that vegetations (meadows) are evenly-distributed and major disturbances have been absent during this period. During 3 decades, the sparse stands at past treeline transformed into closed stands (NDVI increasing from 0.20 to ≥ 0.50), with existing closed stands increasing in area and advancing their upper border. The density of trees in Chirbasa (NDVI 0.1 to 0.3) has gone up whereas in Bhojbasa there is no significant change but the number of groves has increased. The 10 years NDVI data of SPOT-VGT also confirms the same. Near Gaumukh the vegetal activity has not shown any significant change and the same has been confirmed from the NDVI time series data of 10 years. Moreover, the NDVI over the past treeline and past vegetation line are showing greening trend as compared to the reference NDVI, indicating that growth of the treeline apparently exceeded that of the reference.
treeline and had grown denser. The result shows that the treeline is advancing to somewhat higher elevations in response to the climatic amelioration. It was also found that these changes correlated positively with temperature trends (fig.8.7).

Figure.8.5. mean fAPAR in the past decades (1981 to 2001) in Gangotri region.

Figure.8.6. Treeline NDVI time series of 10 years (year 1999 – 2008).
3.3 Net Primary Productivity dynamics at ATE of Uttarakhand

Net primary productivity (NPP), “defined as the accumulation of dry matters by green plants per unit time and space” is very useful in modeling regional and global carbon cycle (Bonan, 1995; Chen et al., 2000). The NPP estimates are important for determining forest growth and production (Milner et al., 1996); impact of human induced land degradation (Wessels et al., 2007); and impact of climate change on terrestrial biosphere (Keeling et al., 1996; Thompson et al., 1996; Nemani et al., 2003). Direct measurement of NPP is time and labour intensive especially for determining spatio-temporal variability of NPP at larger area like Himalaya. It is, therefore, pertinent to estimate NPP through processed based models using satellite data. The longest time series, well calibrated, global data from space based system is available from Advanced Very High Resolution Radiometer (AVHRR) sensors onboard series of National Oceanic and Atmospheric Administration (NOAA) satellites starting from 1982 to 2006. This gridded data with a spatial resolution of 8 Km x 8 Km, is generated by removing cloud contamination and performing atmospheric calibration at the Earth Resources Observation System (EROS). This time series dataset of NDVI and fAPAR has been widely used in last 2 decades for characterization of inter-annual variation in vegetation dynamics at regional and global scale (Goroshi et al., 2015).
A process based model known as CASA (Carnegie-Ames-Stanford) ecosystem model (Yu et al., 2009) is widely used to estimate net primary productivity (NPP). The model estimate NPP based on light use efficiency (LUE) approach. The model calculates NPP as a product of Absorbed Photosynthetically Active Radiation (from NOAA-AVHRR) and biome specific maximum LUE, which is corrected for spatio-temporally varying stress constraints resulting from the temperature and water. The model can be expressed as (Potter et al., 1993) below:

\[
N(x,t) = \sum_r r \cdot S(x,t) \cdot F(x,t) \cdot \varepsilon_{\max}(x,t) \cdot T1(x,t) \cdot T2(x,t) \cdot W(x,t) \quad \text{(8.3)}
\]

Where \( N(x,t) \) is Net Primary Productivity (NPP) over a given location \((x)\) and time interval \((t)\), \((r)\) is the ratio of the solar radiation which can be used by the vegetation with the total solar radiation. \((S(x,t))\) is the monthly total incident solar radiation \((\text{MJ m}^{-2} \text{ month}^{-1})\). \(F(x,t)\) is the fraction of Photosynthetically Active Radiation (fPAR) at location \((x)\) and time \((t)\). \(\varepsilon_{\max}(x,t)\) is the maximum light use efficiency of the vegetation in favourable conditions, \(T1(x,t)\) is the stress coefficient resulting from the extreme low and high temperature to vegetation photosynthesis. \(T2(x,t)\) represents the decreasing trend of LUE of the vegetation when the environmental condition changes from the optimal temperature to a lower or higher temperature. \(W(x,t)\) is the moisture stress coefficient, respectively (Parihar et al., 2014). This model was modified (Goroshi et al., 2015) with biome specific maximum light use efficiency (LUE) and simplified approach for estimating moisture stress coefficient. The modified NPP product (Goroshi et al., 2015) was extensively validated using Eddy flux towers and field measurements. The NPP generated was found having good agreement with Willmott’s index ranging from 0.81 (Evergreen needle leaf forest) to 0.99 (open Shrublands). A linear growth rate of global annual NPP was observed with increment of 0.28 PgC/Year (Goroshi et al., 2015), which is equivalent to 5.7% in the last 25 years. Grid level correlation analysis indicated a strong influence of regional climatic parameters on interannual variability of NPP. The product thus generated for year 1982 to 2006 at 8 Km spatial resolution was taken for investigating the variability of NPP over ATE and interannual NPP change dynamics.
Over Uttarakhand the mean NPP varied from 130 to 187 gC/m²/year in 25 years (1982 – 2006) with a subtle increasing trend (fig.8.8, Appendix.1.4). The increasing CO₂ concentration in the atmosphere is one of the main causes of increasing productivity. The data on annual mean CO₂ growth rate was downloaded (web10) with due credit to Dr. Pieter Tans, NOAA/ESRL and Dr. Ralph Keeling, Scripps Institution of Oceanography (web11). The graph (fig.8.8) shows the annual mean carbon dioxide growth rates (ppm/year) at Mauna Loa observatory (MLO), Hawaii with respect to inter-annual NPP variability at alpine treeline ecotone (ATE) in Uttarakhand. The annual mean rate of growth of CO₂ in a given year is the difference in concentration between the end of December and the start of January of that year. The estimated uncertainty in the Mauna Loa annual mean growth rate is 0.11 ppm/year. The annual growth rate measured at MLO is not the same as the global growth rate, but it is quite similar as observed in India by Bhattacharya et al., (2009) by comparing data from Cabo de Rama near Goa, India. The graph clearly shows that the growth rate of CO₂ concentration matches very well with the inter-annual NPP variability. The increasing trend of NPP also supports the densification happening at the ATE in the study area.

One of the main limiting climatic factors at ATE i.e. minimum temperature is also analysed with respect to increasing NPP at ATE and graph (fig. 8.9) clearly shows that there has been increasing trend of mean minimum temperature at the ATE. This also supports all the above findings about the ingress of treeline to higher elevations and greening trend observed with various independent datasets. As expected the rainfall did not showed very good correlation (fig.8.10) with NPP as the ATE areas are largely not limited by soil moisture. Somehow, during year 1997 to 2006 there exist a good correlation between NPP and Rainfall (fig.8.10). The effects of known drought years in India did not show any impact on the productivity at the ATE.
Figure 8.8: Net primary productivity (gC/m²/year) for 25 years (1982 – 2006) at ATE in Uttarakhand w.r.t. CO₂ growth rate in atmosphere as observed at MLO.

Figure 8.9: Net primary productivity (gC/m²/year) for 25 years (1982 – 2006) and Mean Minimum Temperature (°C) as observed at ATE (Temperature data source: IMD, Pune).
4. Conclusion

Climatic warming is likely to lead to different impacts on the alpine vegetation types along the elevation gradient. The scope of expansion of canopies in past treeline is going to be limited, and increment of NDVI resulting from canopy growth is also expected to be minor. However, the sparse *Betula utilis* forest can rapidly expand its canopy coverage through invading open areas or expanding the canopy within existing stands given a favourable climate change. The treeline forests are expected to get benefitted from global warming but at the cost of loss of biodiversity. This study revealed clearly that there is densification taking place at the current alpine treeline ecotone revealed by means of increasing trend of NDVI, fAPAR and NPP.

The leaf phenology of the area is found controlled with the known drivers of climatic parameters and forms the basis for future investigations on these aspects. There was no evidence of consistent lengthening of length of season or early initiation of the season or late end of season at the ATE which is generally expected in the warming scenarios. This aspect need more investigation from other techniques as, the satellite based sensors may be not able to detect the greenness at very early stage, because NDVI varies with leaf area index and the concentration of chlorophyll, which is not sufficient enough to get detected at very early stage. Moreover, cloud contamination during monsoon also plays the spoil sport during start of the season.