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# Static tree line of Himalayan silver fir since last several decades at Tungnath, western Himalaya

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**Abstract:** The impact of climate change on trees is conspicuous in the form of tree line response at the higher mountain region. Based on tree ring data, we investigated the age stand structure and tree line dynamics of the Himalayan fir (*Abies spectabilis*) at Tungnath, Uttarakhand, western Himalaya. This species forms the upper ecotone limit at ~3335 m asl in association with *Rhododendron campanulatum*, the latter extending further and forming the krummholz ecotone limit. The stand structure and age distribution of fir reveals the presence of high girth class trees at lower altitudes with the oldest tree of ~379 years age at ~3000 m asl. A good number of trees older in age than the age of uppermost tree (~109 years) at ~3353 m asl show the recruitment of fir at the ecotone limit by the early 20th century AD with the shift rate of ~13 m per decade. The highest advancement rate of ~39 m per decade is found during 18th Century AD. Over 300 years old ring width chronology of silver fir indicates that the temperature of winter months, especially February, have positive influence on the tree growth. The presence of trees younger than 100 years within the forest stand near ecotone limit indicates subsequent infilling of forest and also explains the growth behavior of fir trees in relation to increasing temperature of winter months during the last century. Evidences of no regeneration above the present fir limit and the presence of few seedlings within the upper ecotone limit could be related to mixed response to climate and other local factors at this site. In spite of rapid warming silver fir tree line in Tungnath area has not shown upslope advance. It seems that the positive effect of warming in tree growth is nullified by water stress resulting from increased evapotranspiration.

**Key words:** *Abies spectabilis*, climate-growth relationship, treeline shift, tree ring width, Uttarakhand, Western Himalaya.

**Guest editor:** S.P. Singh

## Introduction

In mountainous regions climate has a significant impact on the vegetation growth by defining distribution limits to the species. Global warming influences the natural upper tree line shift to higher elevations due to increase in air and soil temperatures (Holtmeier 2009; Körner 2012; Paulsen & Körner 2014). There are evidences of advancement of natural tree line at some places in the Himalayan region (Dube *et al*. 2003; Gaire *et al*. 2014; Shrestha *et al*. 2014; Tiwari *et al*. 2017; Yadava *et al*. 2017) and other parts of globe (Gehrig-Fasel *et al*. 2007; Kullman & Oberg 2009; Lloyd *et al*. 2003; Moen *et al*. 2004; Moiseev & Shiyatov 2003). The warming trend that followed the little ice age event witnessed unprecedented 20th century warming (Briffa *et al*. 1995; IPCC 2013; Jones &

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Moberg 2003; Mann *et al.* 1999; Pant & Rupakumar 1997) that might have played important role in the tree line shifts. Local site factors, such as physiography, species richness and interactions, herbivory, historical disturbances (natural or anthropogenic) or other biotic factors may also modulate or override the impact of climate on tree line position and responsiveness (Cairns *et al.* 2007; Holtmeier & Broll 2005, 2007; Odland 2015; Payette 2007). In a recent meta-analysis of treeline response to climate warming based on data set of 166 sites, but mostly of Europe and north America, Harsch *et al.* (2009) have reported that since 1900 AD tree line has advanced at 52% of the sites, shown no elevational shifts at 47% sites, and receded at 1% site. Himalayan region though highly vulnerable to climate change (Xu *et al.* 2009) and characterized with variety of treeline structure and growth form (Holtmeier 2009; Schickhoff 2005; Shi & Wu 2013) has remained poorly investigated in terms of tree line response to climate change (Holtmeier & Broll 2007; Schickhoff *et al.* 2015). The analysis of tree line shifting is much complex owing to number of interacting factors which affect the response to climate (Bolli *et al.* 2006; Rössler *et al.* 2008; Schickhoff *et al.* 2015; Vittoz *et al.* 2008). Dubey *et al.* (2003) and Yadava *et al.* (2017) examined the behavior of *Pinus* species from western Himalaya and discussed the control of local site factors along with climate warming for the variable advancement rate at different sites. Studies on Himalayan fir (*Abies*) from Nepal (Gaire *et al.* 2011, 2014; Shrestha *et al.* 2014; Tiwari *et al.* 2017) show mixed response of this species to climate as well other geographic, biotic and landuse factors. We need to generate more data on stand structure and dynamics of the tree line at local species level to improve our understanding of tree line dynamics and factors controlling them. For the present study we have selected *Abies spectabilis,* an important constituent of cool-moist upper temperate to subalpine forests and treeline in Himalaya extending from Afganistan to the eastern parts of India (Sahni 1990). This study from the Indian western Himalaya aims to i) analyze the stand structure of *Abies spectabilis* (silver fir) in treeline ecotone, ii) assess the temporal recruitment pattern and shift rate of this species along the altitudinal gradient, and iii) analyze the temporal growth dynamics in relation to climate. The findings of this study are expected to help in assessing the sensitivity and growth response of this species to the climate change and other causative factors.

## Materials and methods

### *Study area*

Tungnath area (30°′29–30°30′N and 79°12′–79°13′E), is a part of Kedarnath Wildlife Sanctuary in the Garhwal region of Uttarakhand, Western Himalaya (Fig. 1). The area forms the upper catchment (2700–3800 m asl) of river Alaknanda, a principal tributary of river Ganga and has religious importance due to the presence of Tungnath Temple at the altitude of ~3500 m asl. The study area is approachable by motorable road till the small settlement named Chopta at the altitude of ~2800 m asl, followed by mule track to the Temple.

The forest at study area falls under the upper temperate to subalpine zone, which gives way to alpine meadows above the timberline ecotone. The studied altitudinal transect (from ~2750 m asl to above tree line) has preponderance of mesic and shade loving species of conifers (*Abies spectabilis, Taxus wallichiana*) and broadleaved taxa (*Quercus semecarpifolia, Rhododendron arboreum, R. campanulatum, Betula utilis*). *Abies spectabilis,* (D.Don) Mirb, commonly called Himalayan silver fir is tall (upto 50 to 60 m), evergreen conifer with altitudinal range from lower temperate (~2400 m asl) to near alpine zone (4400 m asl) in the Himalayan region (Champion & Seth 1968; Gaire *et al.* 2011; Ghimire *et al.* 2008). In the present study site *A. spectabilis* grows in association with broadleaved taxa, especially *Q. semecarpifolia* (oak) and *R. arboreum* along with other species *viz., Acer caesium, Prunus cornuta, Taxus wallichiana* and *Sorbus foliolosa* untill ~3100 m asl. The dominance of *A. spectabilis* occurs above ~3100 m asl mainly in association with *B. utilis* and *R. campanulatum,* and forms the ecotone limit at ~3335 m asl (Fig. 2). Above fir limit *R. campanulatum* dominates and forms the krummholz vegetation layer on thin soil cover. *Danthonia cachemyriana* is the common grass species, while *Carex* spp. and *Kobresia royleana* represent the major sedges. The area has high influence of anthropogenic activities with frequent disturbance in the silver fir community for construction and fuel consumption (Rai *et al.* 2012). Grazing by sheep, goats, mules and cattle during entire growing season is common in the area.

The three years climate data of (2008 to 2010, Adhikari *et al.* 2011) show long winters (October to April), short summers (May to June) and rainy season (July to September). Near timberline ecotone, the mean annual temperature (MAT) averages around 6.65 ± 0.68°C, ranging between −8.91 and 25.6 °C for January and May, respectively, the

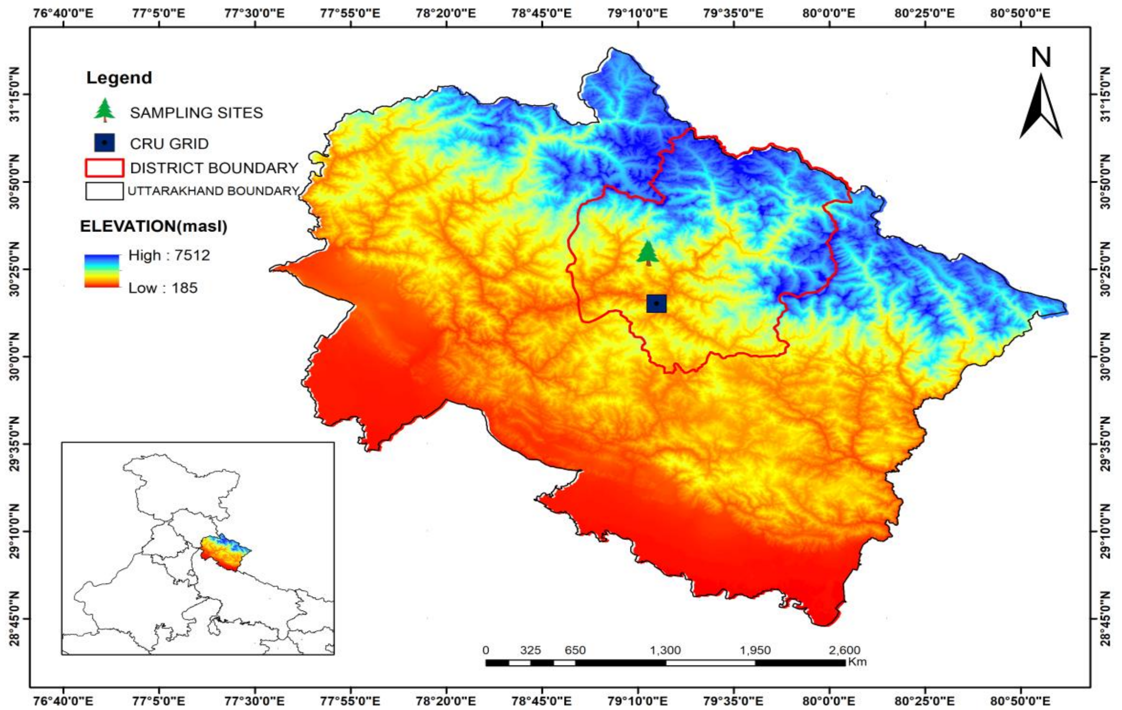


**Fig. 1.** Digital elevation map of Uttarakhand showing locations of study site and source of climate data. Tree symbol denotes the tree sampling site (Tungnath) of *Abies spectabilis*. Solid box denotes the closest grid data point (CRU-TS3.22) of climate.

warmest month being July with mean temperature of 12.56 ± 1.23 °C (Fig. S1). Annual precipitation is 2400 ± 430 mm, of which 89.5% comes through Indian summer monsoon (ISM) during June-September. Snow cover, largely due to westerlies, lasts for 85 ± 22.7 days $yr^{-1}$ during winter months. However, for developing the tree growth climate relationship, the required long term measured climate data are not available for the area. The gridded data for the area from Climatic Research Unit (CRU) of the University of East Anglia [CRU-TS v.3.22; (05x05 degree) grid, available at http://www.cru.uea.ac.uk/cru/data/hrg/)] for the period 1901–2014 CE (Harris *et al.* 2014, Figs. 1 and 3) have therefore been used for developing the tree growth and climate relationship.

## *Field sampling and processing*

About 300 tree core samples of fir were collected in May 2016 and 2018 from 153 silver fir trees growing on the south facing slope between ~2780 and ~3353 m asl along the Chopta-Tungnath transect. Two cores per tree were collected at the breast height (~1.3 m above the base) and for each tree the geographical locations and the girth at breast height (GBH) were recorded. Trees with relatively thick girth were selected to get longer chronological records. Apart from this, 125 fir trees were randomly surveyed and measured for GBH only to assess the girth class distribution. The extracted cores were air dried and then mounted in wooden frames. The upper surfaces of the core were cut by sharp edge razor blade and polished with coarse and fine grade sand papers to enhance the surface resolution of cells of annual rings, which is to make ring boundaries distinctly visible under microscope. Rings of each core were counted under the stereo zoom microscope (Lieca) and each ring was assigned a calendar year through cross dating. To establish the relationship between tree growth and climate, the ring widths were measured to the nearest 0.001 mm precision using the LINTAB-6 measuring system attached to computer with measuring software TSAP-Win scientific version (Rinn 2003). Cross dating and quality check were done using the COFECHA (Holmes 1983) computer program and ring-width chronology was developed. The corrected ring-width data were standardized using the computer program ARSTAN (Cook 1985). Detrending of measured ring widths with negative exponential or linear regression function was done to enhance the common climatic signal and to

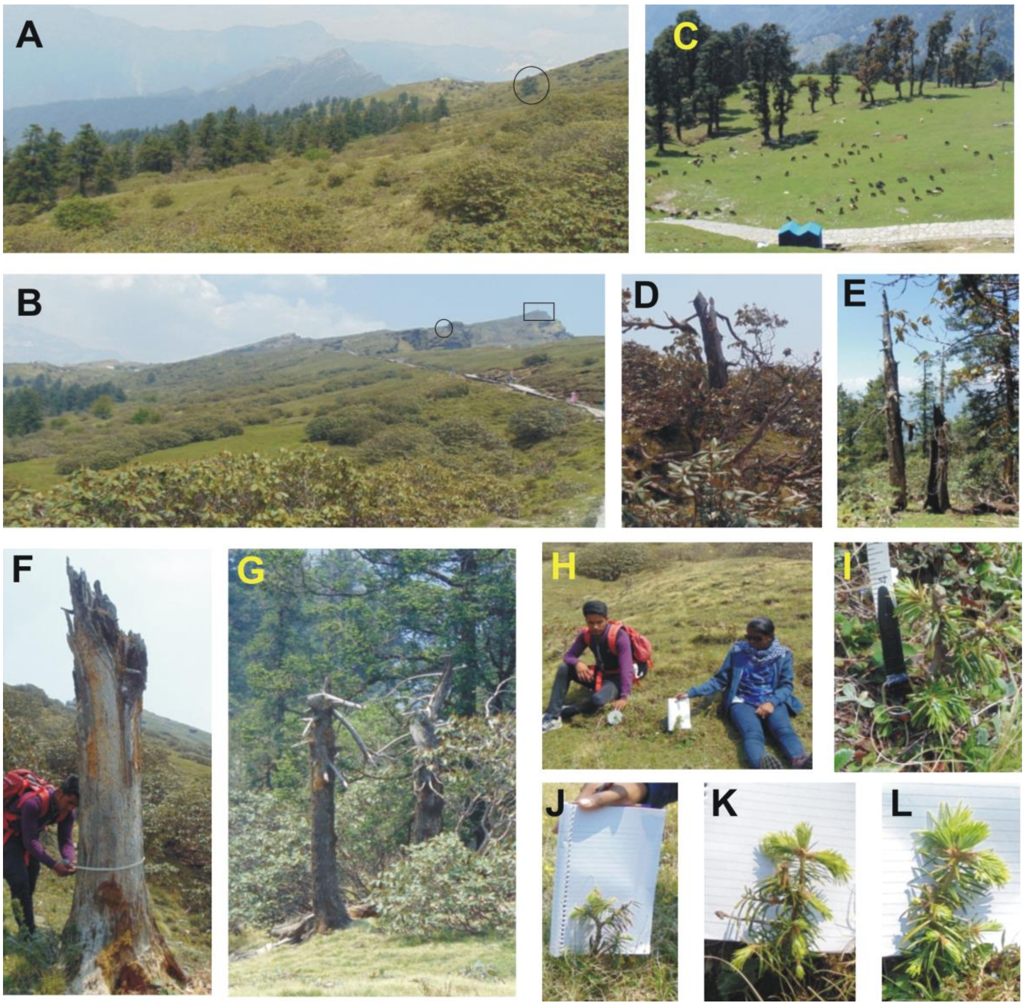


**Fig. 2.** A) Upper ecotone limit of *Abies spectabilis* (fir). Circle denotes the uppermost fir tree recorded at Tungnath transect. B) Topography of the Tungnath transect. Circle denotes the location of Tungnath temple above fir limit. Rectangle shows the highest summit point. C) Growth of *Quercus semecarpifolia* and grazing activity in the meadows along the transect. D to G) Dried and broken stumps of fir near upper ecotone limit of fir. H to C) Growth of seedlings on the slopes near upper fir limit.

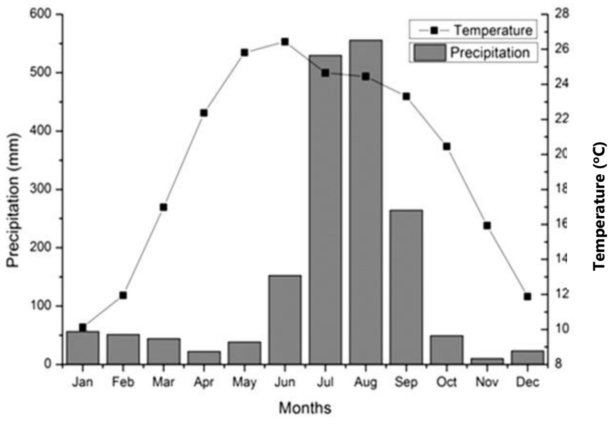


**Fig. 3.** Climate data from CRU-TS3.22 showing monthly mean temperature and precipitation.

remove the low frequency trends due to aging and stand dynamics of the individuals.

## *Growth dynamics and shift rate*

To understand the growth dynamics and altitudinal shift rate of fir, various relationship models were developed amongst the tree diameter at breast height (DBH), tree age and their altitudes. DBH of each tree was calculated dividing the measured GBH (circumference) by the value of π (3.14). Each tree sampled for cores was assigned an age following the standard method of annual ring counts, cross dating and necessary corrections (Camarero & Gutierrez 2004; Gaire *et al.* 2014; Speer 2010). Complete cores of around 120 trees

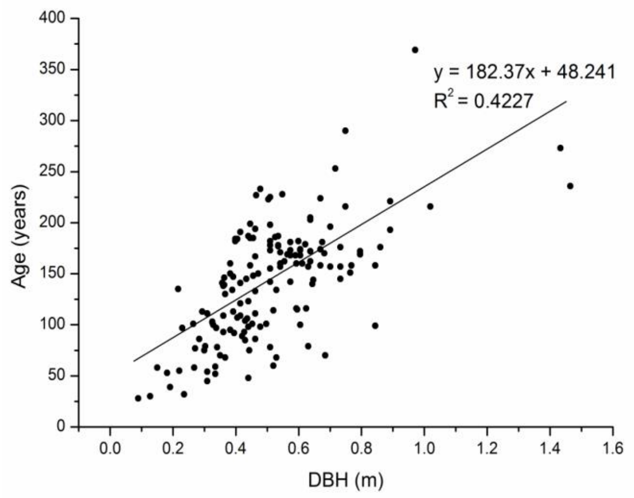


**Fig. 4.** Diameter at breast height (DBH) and Age relationship of *Abies spectabilis* from Tungnath, Uttarakhand.

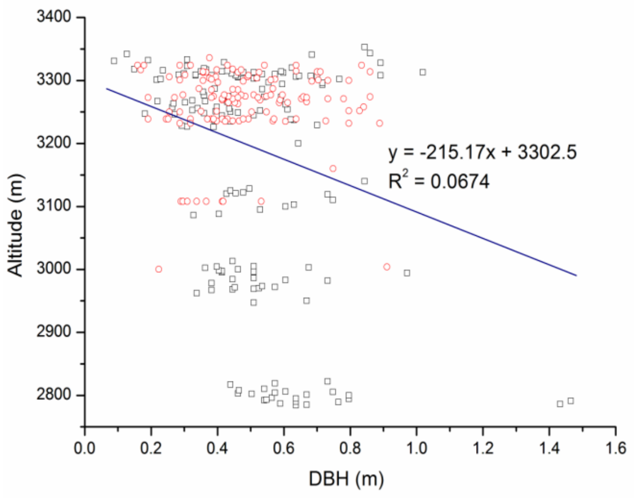


**Fig. 5.** DBH and Altitude relationship of *Abies spectabilis* growing at Tungnath, Uttarakhand. Black squares represent the DBH of fir trees sampled for tree ring cores. Red circles represent DBH of fir trees not sampled for tree ring cores.

having the length from bark to pith were taken to develop the DBH and age relationship model (Fig. 4). To correct the age for the core extraction height, a decade was added to the counted age of each tree (Gaire *et al.* 2011). Some trees with their GBH over 2 meters were found to be rotten and pith length cores were not available. Considering the variation in growth distribution of *A. spectabilis* above and below 3100 m asl altitude, the DBH-age relationship model has also been tested separately for the trees growing above and below the 3100 m asl respectively (Figs. S2–S3). This allowed assessing the stand structure and growth variability of *A. spectabilis* at different elevational levels. The DBH and age regression models were used to estimate the near approximate age of rotten and uncored trees with measured GBH. The girth class and age distribution, and the growth rate dynamics of this conifer has been analyzed by establishing the relationships between DBH and altitude, and age and altitude of the trees using linear regression model (Figs. 5 and 6). Temporal advancement or shift rate of fir to higher elevation has been approximated following the standard calculation (Gamache & Payette 2005; followed by Gaire *et al.* 2014; Tiwari *et al.* 2017 and others) by dividing the difference between the altitudes of uppermost individual and oldest individual with the difference between the age of oldest individual and uppermost individual. Also, to understand the establishment year of *A. spectabilis* at different altitudinal transects and to know the temporal variations in the shift rates, the same were calculated separately by dividing the altitudinal transects into 100 and 200 m bands (Fig. 6).

## Results

### *Upper limit and stand structure of* Abies spectabilis

Along the altitudinal transect of Chopta-Tungnath, *A. spectabilis* forms the upper limit at ~3335 m asl with ±5 meters of altitudinal variation which might be due to local factors. The uppermost tree was recorded at ~3353 m asl altitude. To analyze the stand structure, various correlation analyses were performed amongst age, DBH and altitude and they showed significant correlation values. Correlation between DBH and age was positively significant ($r = 0.64$, $P < 0.05$) with 42% variability explained by DBH (Fig. 4). Correlation between DBH and age was calculated separately for lower (below 3100 m asl) and high (above 3100 m asl) parts of altitudinal transects. For the lower part of transect, regression model based on cores of 54 trees showed positive correlation ($r = 0.53$, $P < 0.05$) explaining only 26% variability (Fig. S2). For 98 trees growing above 3100 m asl the significant positive correlation ($r = 0.67$, $P < 0.05$) explained 47% variability (Fig. S3). The age of around 125 uncored fir trees was calculated using the DBH-age regression model.

All along the altitudinal gradient, DBH ranged from 0.09 to 1.46 m, with lower DBH trees mainly

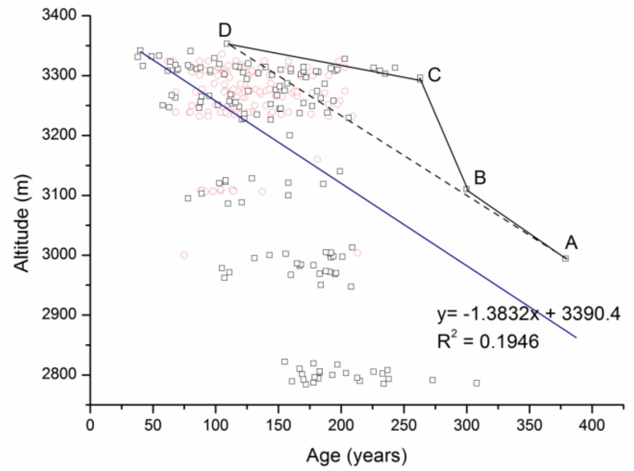


**Fig. 6.** Age and Altitude relationship and shift rate of *Abies spectabilis* growing at Tungnath, Uttarakhand. Black squares represent the measured ages from tree ring cores of sampled fir trees. Red circles represent the calculated ages of unsampled fir trees using the DBH-Age relationship model. A & D marks respectively the oldest and the uppermost growing fir trees. A-D broken line represents the average shift rate from 1637 to 1907 AD. A-B, B-C and C-D solid lines marks the temporal variations in the shift rate of fir along the transect.

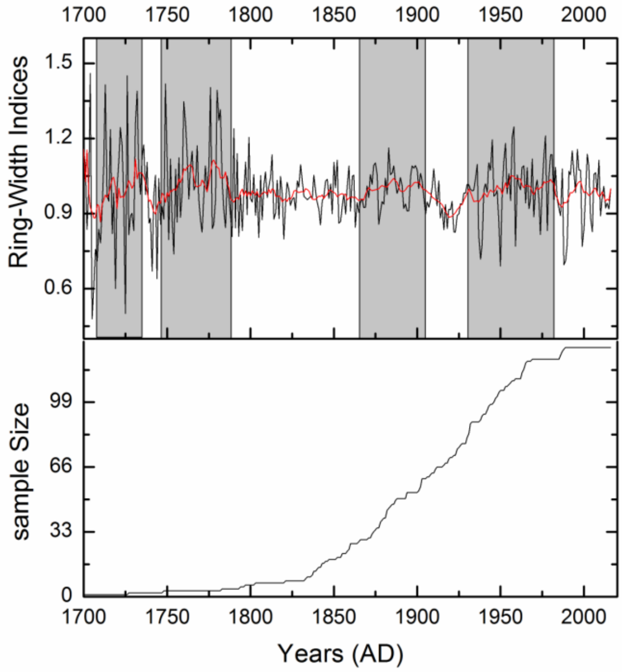


**Fig. 7.** Residual tree ring chronology plot (1700–2016 AD) and sample size plot of *Abies spectabilis* at Tungnath. Grey shaded portions in the ring width indices (RWI) highlights the high radial growth years.

in higher elevations. The correlation between DBH and altitude was found significantly negative (r = −0.34, $P$ < 0.05), indicating decrease in girth size (DBH) of trees with the increase in altitude, but explaining only 7% variability in DBH by altitude (Fig. 5). Though the trees with the highest DBH (1.43 and 1.46 m) were found growing at the altitudes 2786 and 2791 m asl respectively, several high girth class trees were also found towards the upper ecotone limit. Between the altitudinal transect of ~3200 m asl and upper fir limit, the DBH of fir trees ranged from ~0.09 to ~1.02 m.

The correlation analysis between altitude and age (corrected) of ~278 trees, showed significant negative correlation (r = −0.46, $P$ < 0.05) with 19% variability (Fig. 6), indicating the younger trees at higher elevation. The tree of maximum age (379 years, DBH - 0.97 m) was recorded at ~2994 m asl, which is above the altitude of maximum girth trees. Two trees of maximum DBH (1.43 and 1.46 m) were calculated for age ~308 and 314 years, respectively.

### *Shift rate along the altitudinal transects*

The tree ring cores collected from the trees with large girths growing between ~2780 to ~3353 m altitude provided the records of older trees that helped to assess the temporal episodic shift rates within the transect. The age vs. altitude plot (Fig. 6) showed that the oldest tree was ~379 years old (A in Fig. 6) and at altitude of ~2994 m asl, indicating that the species was growing near 3000 m asl altitude at least since ~1637 AD. There were few more trees with age more than 300 years (~308 and 314 years) and they occurred near ~2800 m asl, lower than the altitude of oldest tree. The youngest tree recorded was ~38 years old (GBH/DBH - 0.28/0.09 m) and it occurred at ~3331 m. The age of other young trees was 40 years (GBH/DBH - 0.6/0.13 m), 49 years (GBH/DBH - 0.4/0.13 m) and 55 years (GBH/DBH - 0.97/0.31 m), all growing between ~3332 and 3342 m. The tree growing at the highest elevation of ~3353 m asl was 109 years old (D in Fig. 6). During recent survey in May 2018, we found the existence of few seedlings (5 to 20 cm tall) of fir near ecotone limit within altitudinal gradient of ~3305 – 3338 m asl (Fig. 2), whereas no saplings were observed from the area.

The average shift rate of fir along ~3000 to 3353 m transect (A to D in Fig. 6) was estimated as 13.1 m per decade. However, considering that the youngest individual was recorded at elevation ~3331 m elevation, the average shift rate was calculated as 9.8 m/decade. To understand the recruitment

**Table 1.** Statistics of residual chronology of *Abies spectabilis* from Tungnath, Uttarakhand for the time span 1700–2016 AD.

| | |
|---|---|
| Cores/Trees | 127/86 |
| Mean sensitivity | 0.144 |
| Standard deviation | 0.158 |
| Autocorrelation | 0.026 |
| Mean correlation within trees | 0.382 |
| Mean correlation between trees | 0.177 |
| Mean correlation among all radii | 0.179 |
| Signal to noise ratio (SNR) | 19.151 |
| Expressed population signal (EPS) | 0.950 |

dynamics of fir since mid 17th Century AD, the shift rate was calculated for different altitudinal bands considering the oldest and youngest trees within those transects (Fig. 6). The upslope shift rate of silver fir fluctuated temporally between ~3000 and 3353 m altitude transect. It was ~1.46 m $yr^{-1}$ between 1636 and 1715 AD (A to B in Fig. 6), ~3.95 m $yr^{-1}$ between 1715 and 1772 AD (B to C in Fig. 6) and 0.38 m $yr^{-1}$ between 1773 and 1907 AD (C to D Fig. 6).

### *Tree growth - climate relationship*

A 317 years tree ring width chronology (Fig. 7) was developed from 127 cores of fir trees growing near the ecotone limit. Ring width chronology was transformed into ring width index chronology by removing age trends. Of various detrending methods, negative exponential method provided the significant values for various chronology statistics (Table 1). The residual chronology was used to develop the relationship between tree growth and climate using the software DENDROCLIM2002 (Biondi & Waikul 2004). More than 100 years gridded data (CRU-TS3.22) for mean annual temperature and precipitation was used to develop the relationship. Significant positive relationship was found between the ring width indices and temperatures of previous year November and current year February months (Fig. 8). For precipitation, the relationships were not significant. The observed growth trend (Fig. 7) showed high growth during the early to late 18th century AD with intermittent low growth years from 1738 to 1749 AD. The growth declined after 1790 AD and continued with minor fluctuations till ~1925 AD. Thereafter good growth was recorded with minor decreasing trend in recent years.

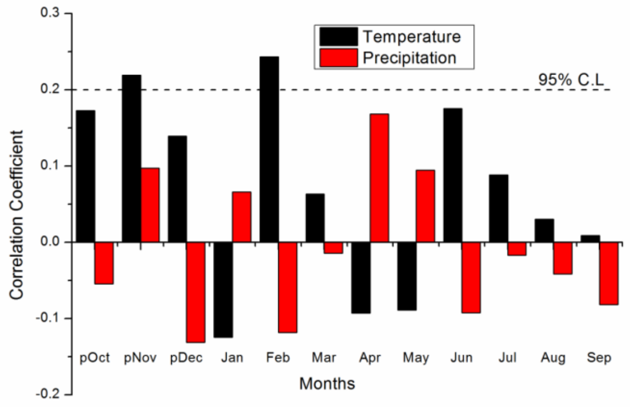


**Fig. 8.** Correlation of Tungnath fir chronology with mean monthly temperature and with monthly total precipitation (1901 to 2014 AD; CRU-TS3.22). Horizontal dashed line represents the 95% confidence level.

## Discussion

### *Stand age structure and tree line dynamics*

The upper limit of *A. spectabilis* ecotone at the Chopta-Tungnath Temple transect is recorded around 3335 m asl which is lower than the reported limits of silver fir in other areas of the central and western Himalaya (Bhattacharyya *et al.* 2011; Gaire *et al.* 2014; Shrestha *et al.* 2014; Tiwari *et al.* 2017). Several reasons could account for the lower silver fir tree line at Tungnath, including summertime grazing, cutting of young trees by local people and also low summit height. Effects of summit syndrome could have substantial role in lowering the timberline elevation, thus, refraining the timberlines to reach their climatically governed limits (Odland 2015). Our data indicate that silver fir occupied ~3300 m elevation during mid to late 18th century and thereafter reached the present elevation of ~3335 m asl by early 20th Century AD with the overall calculated advancement of ~350 meters in ~270 years (from 1637 to 1907 AD). However shift rate varied over time and was highest during the 18th century AD (1715 till 1775 AD). The presence of a ~109 year old tree at the elevation of ~3353 m asl indicates the recruitment of this species by the early 20th century (1907 AD) at that elevation. The elevational distribution of DBH and age (Figs. 5–6) showed that in the treeline ecotone the trees of middle to high girth classes were more in number. This also reported by Rai *et al.* (2012). However, the presence of younger trees aged < 100 years in the forest stand suggests subsequent establishment of silver fir, towards the ecotone limit during the 20th century. The absence of trees or saplings of age less than the age of youngest recorded tree i.e. 38 yrs, indicates no obvious recruitment during the past four decades of rapid warming. Rai *et al.* (2012) also reported the absence of natural regeneration of silver fir community above the fir limit. It shows that the silver fir tree-line remained stable for last four decade. This is contrary to recent tree-line advancement reported from several sites of the greater Himalayan regions of India (Dubey *et al.* 2003; Yadava *et al.* 2017) and Nepal (Gaire *et al.* 2011, 2014; Liang *et al.* 2011; Tiwari *et al.* 2017, etc.). However, analogous to our study the stationary or insignificant shifts have also been reported earlier from some areas of Himalayan and Tibetan regions. From Sygera Mountains (SE Tibet), Liang *et al.* (2011) reported insignificant upslope movement of Smith fir stands at the tree line since mid 20th century but with considerable increase in the stand density. Schickhoff *et al.* (2015) reported similar insignificant alteration in the tree line position and increasing stand density from Rolwaling Valley (Nepal). Despite climatic warming, a near stationary stand structure of silver fir for over several past decades has also been reported by Shrestha *et al.* (2014) and Gaire *et al.* (2011) from central Nepal. A remote sensing based study (Bharti *et al.* 2012) has shown an increase in biomass in a subalpine forest's canopy during 1980–2010 at Nanda Devi Biosphere Reserve, Uttarakhand, but no shift of the upper treeline. From Hengduan Mountains (NW Yunnan), Baker & Moseley (2007) have documented a significant infilling of tree-limit ecocline and upward shift of the timberline since 1923 AD, and argued climate warming as factor for the advancement. However, it was later on detected as an effect of cessation of land use and other human disturbances rather than a result of climate change (Schickhoff *et al.* 2015). Schickhoff *et al.* (2015) estimated 85–90% of treelines to be anthropogenic along the entire mountain arc, and only 10–15% to be orographic/ edaphic and climatically governed. According to Harsch & Bader (2011) at the climatically driven area the trees become progressively smaller and less in age with the increase in elevation. Whereas in the Tungnath area the presence of good number of old trees (> 100 years) might suggest the role of other non-climatic factors in controlling the tree line. Rai *et al.* (2012) discussed the role of anthropogenic activities in the fir community at the Tungnath, as the site is at an approachable altitude. Grazing could also be an important reason for non-survival of seedlings. Shrestha *et al.* (2014) have noticed grazing as main factor for poor regeneration of seedlings. Grazing by herbivores have been taken as an important determinants of tree line position and tree growth and population structure elsewhere also (Cairns *et al.* 2007; Speed *et al.* 2011) and could be a potentially important factor in the mesic area, as young *Abies* individuals have high forage value and may be susceptible to grazing by wild and domestic herbivores (Shrestha *et al.* 2014). In a study in Swiss Alps, land abandonment was reported to be the principal driver of treeline rise, and only a small fraction of upward shift was reported to be due to climate change (Gehrig-Fasel *et al.* 2007). In our study, topography and ground conditions above the present fir ecotone limit at the Tungnath area might not be conducive to the regeneration of fir (Fig. 2). Further, the trees of younger age at the lower elevation (below 3000 m asl) might be the result of clearing of older trees for timber. The low correlation value of DBH–age (Fig. S2) for the fir trees growing at altitude lower than 3100 m asl in comparison to high correlation value for trees growing above 3100 m elevation (Fig. S3) explains non-uniformity in the growth of lower altitude fir trees, which might be due to the competition for space and nutrients from other dominantly growing broadleaved species.

### *Climate growth relationship*

The tree ring width chronology extending from 1700 to 2016 AD built here showed much variation in growth pattern. In the high altitude areas temperature seems to be an important factor in controlling tree growth and tree lines changes (Cook *et al.* 2003; Grace *et al.* 2002; Gunnarson & Linderholm 2002; Payette 2007). The positive response of tree growth to winter temperature observed in this study is similar to some other sites of Himalaya viz. western Himalaya (Borgaonkar *et al.* 2009; Yadava *et al.* 2017), Nepal (Bräuning 2004, Chhetri & Cairns 2016), Sikkim (Bhattacharyya & Chaudhary 2003) and Tibet (Liu *et al.* 2012; Wang *et al.* 2008; Yang *et al.* 2014). The increased temperatures in winter and early spring might favor photosynthesis and other physiological activities that lead to early initiation of cambium formation and division (Fritts 1976; Tranquillini 1964). The low winter temperatures at the higher elevations retard growth by causing bud damage, reduced root activity, and frost desiccation (Wang *et al.* 2008). The comparison of ring width

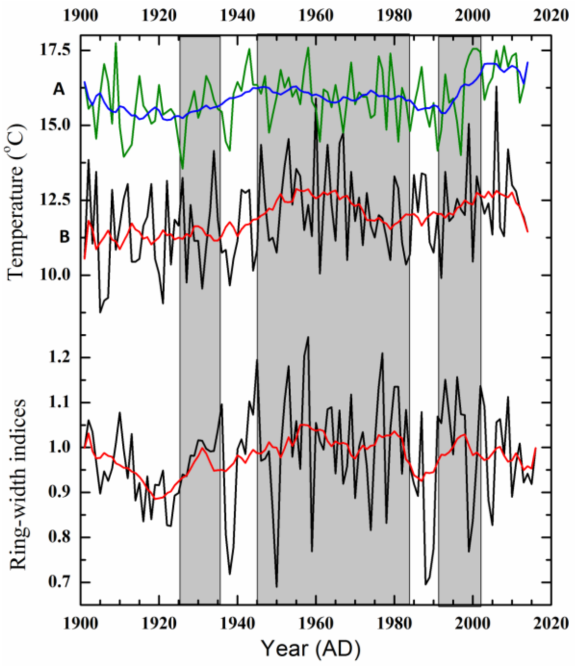


**Fig. 9.** Plots showing comparison of mean temperature (1901 to 2014 AD, CRU-TS3.22) of November (A) and February (B) months with residual ring width chronology (1901 to 2014 AD) of Tungnath fir. Grey shaded portion highlights the years with high radial growth and years with high mean monthly temperatures blue and red lines represents 11 year moving average.

chronology developed here with that of *A. spectabilis* from the other Himalayan regions (Chhetri & Cairns 2016; Gaire *et al.* 2014; Sano *et al.* 2005; Shekhar *et al.* 2017) shows similarity in growth patterns. The high and low radial growth years throughout the chronology might correspond respectively to warm and cool winter months of the years. High radial growths in most of the years during 18th century (1710–1735 and 1747–1785 AD) in this study (Fig. 7) might be due to winter warming reported from several sites of the south Asian regions. Sano *et al.* (2005) based on *Abies* chronology from western Nepal reported a warming trend from 1750 to 1790 AD during pre-monsoon months that reverted to cool conditions subsequently ~1810. Shekhar *et al.* (2017) reported significant reduction in mass balance of Himalayan glaciers during past 400 years, using fir chronology from Dokriani valley, Uttarakhand, indicating increased winter warming. Cook *et al.* (2003) in his October–February temperature reconstruction from Nepal also showed general warming trend over past 400 years. The 18th century warm conditions might have enhanced the growth of fir, this also corresponded with the calculated high shift rate of fir at the Tungnath area. Subsequent below average radial growth from 1795 to 1870 AD, also corresponding to reduced shift rate, might indicate winter cooling episode. Gaire *et al.* (2014) from central Himalaya reported low radial growth between mid and late 19th century AD and from 1940 to 2003, the latter time span of tree growth contrasts to high growth from 1945 to 1986 AD in our study, which might be due to local factors playing role in growth responsiveness. The high radial growth from 1870 to 1910 in our chronology also correlates with the warmest periods of reconstructed temperature of Nepal in tree-ring studies (Chhetri & Cairns 2016; Cook *et al.* 2003; Sano *et al.* 2005).

The growth trend of silver fir during last century (1901 till 2014 AD) has also been compared with the CRU-TS3.22 mean temperature data of November and February months. These two months are reported to have significant role in the growth of fir in this region. A continuous increasing trend in the mean temperature of November and February from 1901 to 2014 AD shows a near synchrony with the growth pattern of this tree (Fig. 9). Increased tree growth during 1925–1936, 1945–1986, 1992–2003 with the intermittent below average radial growth periods during 1911–1924, 1937–1944, 1987–1991, correlates with high and low temperature years respectively. Similar growth trends since last century has also been observed in the Himalayan fir from other studies (Borgaonkar *et al.* 2011; Chhetri & Cairns 2016; Singh & Yadav 2000) and Tibet (Liang *et al.* 2011). Temperature analysis over the Indian subcontinent (Hingane *et al.* 1985) also supports warming winter which could be the reason for high radial growth. Interestingly, no increased growth trend has been observed since 2003 onwards despite observed high mean temperatures of November and February months. This might be attributed to site-dependent controlling factors or to high temperatures crossing the threshold limit of the optimum tree growth at the site as also evident by the presence of few dried-broken stumps of fir trees (Fig. 2) as well as few inside rotten trees. At the lower altitudes warming might have induced increase in the evapotranspiration and reduced the photosynthesis due to intensified pre-monsoon drought. Regeneration of fir after a gap of few decades, discussed earlier by the existence of few seedlings on slopes near the fir ecotone limit might indicate recent changes in local conditions such as restriction of grazing or conducive growth environment due to forest canopy structure and other protective ground features.

## Conclusions

Our study indicates that climate as well as other local factors have significant role in the growth and tree line dynamics of *Abies spectabilis* at the Tungnath area for past 300 years. This study thus justifies the importance of area specific control on tree growth response that can have vital relevance in assessing tree growth dynamics and predictions in regional aspects. At this site fir reached its present upper ecotone limit by the early 20th century with the average shift rate of ~13 m per decade. High shift rate of fir during 18th Century AD, and subsequent decline, corresponds well with the high and low growth trends during this time period. Amongst several factors, winter warming could have played an important role for the high growth and advancement of fir to upper elevations. The occurrence of fir trees younger than 100 years within the forest ecotone limit might be the result of observed increasing trend in the winter temperature during the 20th century. However, gap in the regeneration of fir for last four decades contrasts with the continued winter warming trend. The increased land use pressure for last few decades might also have played a significant role in the stability of fir ecotone limit and could be reasoned for poor regeneration. Recent year regeneration of fir by the presence of few seedlings near the ecotone limit could indicate regeneration and advancement of fir in the Tungnath area. But the continued land use might also play role in tree line dynamics and thus needs future monitoring on the overall survival and growth of fir in relation to climate and other factors.

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## Supporting Information

Additional Supporting information may be found in the online version of this article.

**Fig. S1.** Climate data of Tungnath, Uttarakhand. (After Adhikari *et al.* 2011).

**Fig. S2.** DBH and age relationship of *Abies spectabilis* growing at the elevation lower than 3100 m asl at Tungnath, Uttarakhand.

**Fig. S3.** DBH and age relationship of *Abies spectabilis* growing at the elevation above 3100 m asl at Tungnath, Uttarakhand.