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Growth response of Scots pines in polar-alpine tree-line to a warming climate

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ABSTRACT

Coniferous trees at the alpine and polar tree lines of the Northern Hemisphere represent the outermost limit of their ecological range. Under such conditions, even small temperature variations may cause growth responses, which therefore can be used as indicators for changing environmental conditions. In this study we analysed the radial growth of Scots pine (*Pinus sylvestris* L.) along a latitudinal and altitudinal gradient at six locations in the polar and alpine tree-line ecotone in Finnish Lapland. We evaluated the effect of climatic trends on pine growth in relation to tree age and region, specifying a northern and a southern region in the study area. We found a response of Scots pine to climatic variations until the 1980s, but not to the current warming period. Increasing growth trends could be detected since 2000 in the radial growth of southern located trees, predominantly of juvenile ages, while the northern trees did not respond significantly to the current warming. In the north recent warmer and wetter conditions during winter time, inducing snow loads, wind damages, diseases and frost damages possibly masked the benefits of warmer conditions. The missing link between warming and radial growth would affect the use of tree-rings as proxy for past climate and for predictions for forest extension in polar-alpine tree-line sites.

1. Introduction

Coniferous trees at the alpine and polar tree lines of the Northern Hemisphere grow close to the limit of their ecological range. They have adapted to low temperatures, short growing seasons, and harsh conditions during winter (Heikkinen et al., 2002; Seo et al., 2010). In northern Fennoscandia, where water is sufficiently provided and the competition for light and nutrients is lower than in dense forests, temperature is the most regulating and limiting factor for growth and regeneration (Briffa et al., 1990; Esteban and Jackson, 2000; Heikkinen et al., 2002; Juntunen et al., 2002). Under such conditions, even small temperature variations may cause growth responses, which therefore can be used as indicators for changing environmental conditions (Grace et al., 2002; Linkosalo et al., 2009; Høgda et al., 2013; Salminen and Jalkanen, 2015).

Findings of sub-fossil logs of Scots pine beyond the current timberline refer to a warmer climate and the existence of ancient forests at higher altitudes and latitudes than today (Autio and Heikkinen, 2002; Eronen et al., 2002; Kultti et al., 2006). Since atmospheric warming has been observed in the 20th and 21st centuries in the entire Northern Hemisphere, but particularly in high-latitude regions during the winter season (Klein Tank et al., 2002; ACIA, 2005; Høgda et al., 2013; Aakala et al., 2014; IPCCa, 2014; IPCCb, 2014), a response of tree growth and tree regeneration is expected with ongoing increasing temperatures. In fact, a greening of the arctic has already been detected in several studies due to a densification and upward and northward expansion of the forest area (e.g. Jeong et al., 2012; Pearson et al., 2013).

This trend may have both positive and negative feedbacks on the global climate system. On the one hand, the enrichment of biomass in the previously sparsely covered tree-line ecotone and the replacement of graminoids by shrub and tree vegetation lead to increasing carbon sequestration compensating anthropogenic emissions (Watson, 2000). On the other hand, forest vegetation absorbs incoming solar radiation to a greater extent than alpine fjell vegetation, predominantly during the snow-covered season. This may cause a net warming effect in ecosystems and on larger scale initiate circulation changes in Arctic regions (Grace et al., 2002; Wramneby et al., 2010; Jeong et al., 2012; Miller and Smith, 2012; Zhang et al., 2013). Tree abundance additionally increases evapotranspiration, resulting in enhanced moisture in

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the troposphere and further global warming (Swann et al., 2010; Jeong et al., 2011; Pearson et al., 2013).

More research is needed to reliably estimate the adaptation of conifers to a changing climate and to derive realistic models of forest expansion into current tundra and alpine regions. Consequently the aim of the present study is to analyse the growth of Scots pine (*Pinus sylvestris* L.) in the polar and alpine tree-line ecotones in Finnish Lapland in relation to regional climate. In order to do this: (1) We investigated tree growth along an altitudinal gradient at six locations to determine spatial growth differences of pines across northern Finland. We evaluated the effect of latitude and altitude on current pine growth and detected the most relevant climatic drivers. (2) We also investigated the impact of long-term climatic trends on pine growth with regard to age and region in Finnish Lapland. We hypothesized that tree growth has increased during the last decades due to more favourable growth conditions especially in the northern region, where temperature is the most limiting environmental factor. We expected the climate-sensitive and fast-growing juvenile trees to respond to a greater extent with increasing radial growth to warming temperatures than mature trees.

2. Material and methods

2.1. Study area

In the study area in Finnish Lapland, coniferous tree lines are of alpine or polar-alpine character and located on gently sloping hills with altitudinal limits of 200–500 m a.s.l. The forest-line ecotone is primarily formed by a widespread homogenous vegetation pattern of Scots pine and Mountain birch (*Betula pubescens* subsp. *czerepanovii*) (Heikkinen et al., 2002; Kultti et al., 2006). The regional climate is influenced by the North Atlantic Ocean and the Scandes Mountain range, with a maritime climate in the coastal regions and (sub)continental conditions towards interior Finland (Linderholm et al., 2010). Cold winters and relative warm summers define a growing season of less than four months (+5 °C threshold) including July as the warmest month of the year. The temperature sum varies from 800 to 900° days in the south to <600° days in the north of the study area. The annual mean precipitation varies from 300 mm in the winter period and 700 mm in the summer period (Finnish Meteorological Institute, 2016). Due to low temperatures and evaporation rates, sufficient water supply is provided in the entire study area (Autio and Heikkinen, 2002). A permanent snow cover lasts from October to May (Kultti et al., 2006).

2.2. Sampling design and data preparation

The sampling was carried out in August 2014 and 2015 in six locations in Finnish Lapland (Fig. 1), where a long-term tree line monitoring project had already been established in 1983 by the Finnish Forest Research Institute (Metla) and the universities of Oulu, Helsinki and Turku (Juntunen et al., 2002). The project was designed to study regeneration and stand volume in both the polar and the alpine tree-line ecotone and is now complemented by this study. The locations were chosen on a latitudinal gradient from northern to southern Lapland and included three sampling plots each, placed along an altitudinal gradient in the closed forest zone, the forest-line zone and near the tree line (Fig. 2), resulting in total of 18 sites. The three sampling plots in each location were located close but in at least 100 m distance from each other and differed in vegetation pattern, tree height and stand density (Fig. 2). The forest-line zone was defined here as the altitudinal limit where the forest canopy closure ceases (Hustich, 1948), whereas the tree-line zone was characterized by between-tree distances of more than 2 m up to 100 m. The tree-line zone was located at 450 m a.s.l. in the southernmost location and at 200 m a.s.l. in the northernmost location. Healthy solitary pine trees of various ages which did not show any sign of damage, deformation or disease were chosen for the dendroecological sampling. To avoid remarkable signals of the stand structure in the tree-ring data, we focussed on isolated, unsheltered trees for sampling. We recorded each sample tree and bored two cores with an increment borer at breast-height. In each site, 30–60 trees were sampled, generating a dataset of at most 180 sample trees for each location. The dataset contained a total amount of 963 sample trees.

The sampled increment cores were mounted on sample holders and polished with sandpaper and razor blades to make wood anatomical structures and tree-ring boundaries clearly visible. The samples were scanned with a high-resolution (3200 dpi) flatbed-scanner and the ring-widths measured by using the software *CooRecorder* and *CDendro* (Cybis Elektronik & Data AB, 2008). If a reliable detection of the rings was not possible in the scan, the ring-width measurement was performed by using the LINTAB™ measuring station (Rinntech, Germany). The samples were divided into groups by site and cross-dated within the groups by using the software TSAPWin (Rinn, 2010). The cross-dating contributed to detect measuring errors, missing rings, and to evaluate the synchronicity of the single series. To reduce statistical noise and to strengthen the climatic signal, sample trees with signs of damage, compression wood or extensive parts of missing rings were excluded from further analysis. Thereby, a total amount of 905 sample trees remained for constructing the final chronology.

2.3. Tree-ring analysis: site-specific growth variations

The ring-width measurements were used to compute the mean annual growth rate of pine, the annual increase in the stem radius, for each of the 18 sample plots. This was done in order to point out site-specific differences in the climate, stand structure or disturbance regime. The computation was based solely on juvenile trees, established in the forest stands after 1950, since they reflect the impact of climate and stand structure with a high sensitivity in the tree-ring data. Furthermore, the mean growth rate of mature trees would be affected by the biological age curve, forming wide rings in fast-growing juvenile ages but narrow rings in the mature ages. By using only juvenile ages we aimed to reduce the impact of the biological age. The statistical significance of the results was tested by the two-way factorial analysis of variance (ANOVA) with zone and location as factors on a confidence level of $p < 0.05$.

For further analysis, we transformed the raw ring-widths of all mature and juvenile samples of each site into a site-specific residual chronology to enable a comparison of the high-frequency growth-pattern. Since this method eliminated the age effect, trees of all ages were included. The age-related growth trends and non-climatic noise, such as local disturbance events by pests or diseases were first removed from the tree-ring data by standardization with the dplR package in R version 3.2.0 (Bunn et al., 2015). Dimensionless tree-ring indices were derived by dividing each measured ring-width value by the expected value of the growth curve (Cook and Holmes, 1986). Since no uniform age-trend was visible in the predominantly juvenile samples, a relatively flexible smoothing spline function of 30 years and a frequency cut-off of f = 0.5 was fitted to the individual series. The individual index series were then averaged by site into 18 residual chronologies (Cook and Holmes, 1986), being cleaned from autocorrelation for the climate analysis. Descriptive statistics, such as the mean tree age, mean sensitivity (MS) and signal-to-noise ratio (SNR) were computed. The Expressed Population Signal (EPS), as a function of sample size and mean inter-series correlation (RBar), indicated the reliability of the chronology (adequate when EPS $\geq$ 0.85) (Wigley et al.,