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Response of radial increment variation of Scots pine to temperature, precipitation and soil water content along a latitudinal gradient across Finland and Estonia

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ABSTRACT

In the Nordic countries, temperature and precipitation regimes are predicted to change as a result of climate change, which may reduce water availability and thus tree growth. This study presents a spatial approach for analysing variations in the annual radial increments of trees across a latitudinal transect. The aim was to evaluate the importance of daily temperature, precipitation and soil water content as regulators of tree growth across a north-south gradient. Increment cores were collected from living Scots pine (*Pinus sylvestris* L.) trees growing on dry and sandy soils in five regions in Finland and two regions in Estonia. A total of 1 024 trees were measured across 551 sample plots. No clear latitudinal trend was evident in the magnitude of the correlation between the variations in annual increment and the current summer's temperature, but the time period most strongly related to the increment variation shifted towards earlier dates with a decrease in latitude southwards. Thus, the results challenge the traditional findings that the growth of trees located at lower latitudes is less affected by temperature. Moreover, the results demonstrate the importance of using high-resolution weather data when analysing variations in the radial increments of trees. In all of the regions, including the high northern latitudes, high precipitation in the current summer promotes tree growth, and the correlation between summer precipitation and the increment variation increases with a decrease in latitude. The correlations between increment variation and soil water content estimated using two different models were lower than those involving precipitation. The results suggest that accurate soil information is needed to describe the connection between water content and tree growth.

1. Introduction

During recent decades, various human-induced threats (e.g., acid rain, climate change) have caused a range of direct and indirect environmental changes, and as a result, the rates of forest ecosystem processes have been altered (e.g., Olesen et al., 2007). In the Nordic countries, climate change is expected to increase tree growth and forest production (Kellomäki et al., 2008; Seppälä et al., 2009). In several regions, climate change may, however, reduce water availability intermittently because of increasing variability in precipitation (Fischlin et al., 2009; Jylhä et al., 2009). Increasing temperatures will also increase the evaporative demand, which may reduce tree growth and forest production and increase forest damage (Mäkinen et al., 2001).

The analysis of tree rings has played a highly significant role in the evaluation of past climate variations (e.g., Schiermeier, 2010). Studies examining the climate-growth relationships along ecological gradients have demonstrated that differences in growth responses among different environments must be considered (e.g., Briffa et al., 1987; Hofgaard et al., 1999; Ciais et al., 2005; Berner et al., 2013). According to previous studies conducted in the Nordic countries, the temperature in July is strongly related to the annual increment variation of Scots pine, followed by the temperatures in June and August (Mikola, 1950; Elfving et al., 1996; Mäkinen et al.,

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2002). However, the proportion of increment variation accounted for by the variation in summer temperatures has been observed to gradually decrease along a north-south gradient (Lindholm et al., 2000; Mäkinen et al., 2001; Helama et al., 2005). In northern Finland, the growth response to precipitation is weak (Lindholm, 1996; Salminen et al., 2009; Korpela et al., 2011), but a fairly high correlation between summer precipitation and the increment variation of Scots pine has been observed in southern Finland and Estonia (Henttonen, 1984; Helama et al., 2005; Hordo et al., 2011).

The traditional approach for studying the climatic signal contained in tree rings has been to relate monthly mean weather data to tree-ring series without considering growth as a dynamic process (Fritts, 1976). However, climatic events that occur at scales other than complete calendar months may explain growth variations substantially better. In a previous study (Hordo et al., 2011), we have demonstrated that weather variables averaged over shorter periods (10 days or half-months) are advantageous for detecting the periods that most influence radial growth. Moreover, Korpela et al. (2011) have utilised even higher-resolution data (daily mean temperatures and the estimated daily photosynthetic production) and found that, in northern Finland, the periods that most influence radial growth begins in late June and extends to late July.

At high latitudes and altitudes, climatic factors, especially temperature, trigger the onset of radial growth and regulate the growth rate during the growing season (Seo et al., 2008; Jyske et al., 2012; Lupi et al., 2012). In earlier studies, we have found that the onset of tracheid production varies from late May in southern Finland to mid-June in northern Finland (Mäkinen et al., 2008; Jyske et al., 2014). Schmitt et al. (2004) have found that tracheid production does not start until the last week of June in the northernmost areas of Finland. Tracheid production also ends earlier in the northern stands (Jyske et al., 2014). These results imply that Scots pine is able to adjust the timing of radial growth according to the local conditions and, therefore, the factors and the most influential time period may differ between regions.

Despite the fundamental nature of the growth process, our present knowledge concerning the linkages between tree growth and environmental drivers is still fragmentary, especially our understanding of the dynamic interplay between tree growth and actual resource availability. In this study, we evaluated the variations of the annual radial increment of Scots pine and weather – analysing growth relationships along a latitudinal transect from northern Finland through southern Finland to Estonia. Specific emphasis was given to the weather variables that are predicted to change considerably as a result of climate change. This emphasis entailed the evaluation of the importance of daily temperature, precipitation and soil water content as regulators of tree growth across the north-south gradient. We also aimed to identify the time intervals during which daily temperature, precipitation and soil water content are most strongly linked with the radial increment of Scots pine. Because the impact of prolonged droughts on tree growth is not well known in the Nordic countries, we concentrated on dry sites assumed to be drought prone. In addition, we assessed the predictive power of two water balance models (Laurén et al., 2005; Peltoniemi et al., 2012) for describing growth variations. Our key hypotheses were as follows: (1) the limiting effect of low temperature is greater in the north, while (2) the importance of water availability increases to the south; (3) when moving from north to south, the time period that most influences radial increment shifts to earlier dates, and (4) the soil water content estimated using soil water models describes the availability of water to trees better than precipitation and is, therefore, more closely related to the variation in growth.

2. Materials and methods

2.1. Tree-ring data

As part of the National Forest Inventory (NFI) run by Metla since 1921, a large, geographically representative sample from Finnish forests has been monitored (Tomppo et al., 2011). The increment cores for this study were collected from Finland for the NFI during the years 1996–2008. The major strength of the inventory data is the high number of sampled stands, based on a systematic cluster sampling scheme scattered across Finland. As the inventory design is based on sampling, the results are statistically representative for the basic population. In the NFI, a number of variables describing the sample trees and sites are available. Thus, the data can be stratified in a number of ways producing sub-groups with a small within-strata variation. For this study, plots on sandy and coarse-gravelly soils located at relatively infertile sites (*Vaccinium*, *Empetrum-Vaccinium*, and *Empetrum-Myrtillus* site types (Cajander, 1949)) and at infertile sites (*Calluna*, *Empetrum-Calluna*, *Myrtillus-Calluna-Cladina*, and *Cladina* site types) were selected.

The selected sites encompassed five climatically different regions of Finland (from the north to the south: Sodankylä (SO), Oulu-Pohjanmaa (OP), Pohjois-Karjala (PK), Etelä-Pohjanmaa (EP), and Etelä-Karjala (EK)) (Fig. 1). In each region, the 100 plots closest to the centre of the region were selected for the data set. At each NFI plot, tallied trees were selected using the angle-gauge method (Bitterlich, 1984), but the largest trees were sampled as a fixed-radius plot (Tomppo et al., 2011). On every seventh tree, one increment core from the bark to the pith was collected at breast height (1.3 m). The trees with less than 30 rings were excluded from this study.

In Estonia, a total of 51 permanent, growth and yield plots located on dry sandy soils (*Calluna*, *Cladonia*, and *Vaccinium* site types) were selected from North-East Estonia (NE) and Hiiumaa Island (HI) (Fig. 1). Outside of each plot, up to 8 dominant trees that had no severe damage were randomly selected. Two increment cores were collected from opposite sides of the tree at breast height.

The number of trees sampled in each region ranged from 120 to 263, and the mean height of the sampled stands ranged from 12.8 m to 18.3 m (Table 1). The ring widths of the cores collected from the sample trees were measured to within 0.01 mm and visually cross-dated. This cross-dating was verified using the COFECHA software (Holmes, 1983; Grissino-Mayer, 2001). A total of 1024 trees were measured from 551 sample plots, but five Finnish trees were excluded because they could not be cross-dated. The ring-width series were detrended by applying the negative exponential model to each tree. An autoregressive (AR) model was used to remove autocorrelation from the detrended chronologies (prewhitening) using the ARSTAN software (Holmes et al., 1986). Finally, the annual increment indices for each region were computed as the mean of the individual prewhitened series. The sampling, measurements, data set, and detrending are described in detail in Hordo et al. (2011).

2.2. Meteorological data

The data of the closest weather station with daily weather data were used for each region (Table 1). These weather stations are maintained by the Finnish Meteorological Institute (FMI) and the Estonian Environment Agency (EEIC). The daily mean, minimum and maximum temperatures, and the daily precipitation sum were available for period from 1960 to 2005. In regions PK and EP, the weather data from two stations located close to each other were used to cover the entire period.