Annual Growth Variation of Scots Pine in Estonia and Finland

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Abstract

This study presents the results of a dendrochronological and dendroclimatological study of Scots pine growth on dry sites in Estonia and Finland. Increment cores from two regions in Estonia and from five regions in Finland are used. The cores were collected from living trees nearby permanent research plots in Estonia and from the National Forest Inventory (NFI) plots in Finland. A total of 1,024 trees' radial growth was measured in 551 sample plots. The relationship between two types of standardized index series (regional growth curve RGC and negative exponent curve EXP) and weather parameters derived from daily data was characterized by correlation analysis. According to the location of studied sites (regions), positive correlation of precipitation and negative correlation of temperature (e.g. spring temperatures, drought etc) to the radial growth of Scots pine trees was found. A similar climate impact to the radial growth in mean temperature and the sum of precipitation in August of the previous year was found in several regions (HI, EK, OP, PK), which means that drought could be the main growth limiting factor in several regions. The correlation between spring temperature (mid-March – early-April) and diameter increment seems also to be positive and significant in some regions (HI, EK, EP, OP, SO). Cropper method was applied to pointer year analysis in different regions. According to the analysis, 1967 and 2000 were the most significant positive pointer years in several regions; and 1969 was a negative pointer year in five regions. Therefore, weather prerequisites for tree growth are expected to change gradually from south to north regions.

Key words: correlation analysis, increment cores, permanent research sample plots, NFI, radial growth, biogeography, Cropper method

Introduction

Growth variation of trees and its response to climatic and environmental factors provide information on the present and past environment, particularly in the areas where tree growth is sensitive to climate factors (e.g. Fritts 1976, Levanič and Eggertsson 2008). Therefore, the radial growth responses of trees to weather and climatic variations have been studied in many countries. Growth limiting factors like temperature, radiation and precipitation vary from region to region and year to year (e.g. Helama and Lindholm 2003, Hordo et al. 2009, Vitas 2008).

Throughout Europe, Scots pine (*Pinus sylvestris* L.) has widely been used in dendroclimatological research and climate reconstructions (e.g. Bogino et al. 2009, Läänelaid 1997, Mäkinen 1998). Scots pine is one of the most comprehensively investigated tree species also in the Baltic and Nordic countries (Erlickytė and Vitas 2008, Hordo et al. 2009, Läänelaid and Eckstein 2003, Lindholm et al. 2000, Lindholm et al. 2009, Mäkinen 1998, Pasanen 1998, Pärn 2002, Pärn 2008, Zunde et al. 2008). Different factors control its growth in climatically different regions (Cedro 2001, Helama and Lindholm 2003, Vitas and Erlickytė 2007). The relationship between weather and growth is not easy to explain, because short- and long-term weather events as well as local ecological conditions affect growth differently (Schweingruber 1996). It is necessary to consider the entire operational environment of the tree and the various effects of factors on processes occurring at different times in the year, and in different parts of the tree (Fritts 1976).

However, spatial comparison of time series in tree growth enables the identification of environmental driving forces of growth variation and the underlying mechanism behind it. Spatial and temporal gradients also offer possibilities for formulating more specific hypotheses on the effect of climate change on tree growth over time (Mäkinen et al. 2002). Relatively little research has focused on comparing dendrochronological records between Finland and Estonia. Understanding the natural dynamics of pine forests and the factors affecting tree growth within these forests is an important management issue. Varying weather conditions and the length of growing seasons should result in strong climate signals. However, disturbance and competition can also have major impact on tree growth. Therefore, the variability in tree-ring series depends on internal and external factors such as climate, competition and their interactions (Piutti and Cescatti 1999). The strong association between tree growth and weather variables indicate the potential usefulness of this pine species in dendroclimatic studies. The comparison of data from several sites will identify common changes in tree growth, which represents important evidence of large, regionally representative climate-based growth changes. Regional differences between sites indicate local differences in growing conditions.

The aim of the study was to compare the growth variations and identify pointer years of Scots pine growing on dry and sandy sites in different regions in Finland and Estonia. Furthermore, we analyzed annual growth responses to weather variations, including weather variables derived from daily data.

Material and methods

Tree ring data

We used the increment cores of Scots pine trees on dry and sandy sites from two regions in Estonia and five regions in Finland (Figure 1). In Estonia, a total of 51 permanent growth and yield plots in dry and sandy soils (*Calluna*, *Cladonia* and *Vaccinium* site types) were selected from North-East Estonia (NE) and Hiiumaa Island (HI) in 2007 (Hordo et al. 2009, Sims et al. 2009). Outside each plot, up to 8 dominant trees without severe damage were selected. From each selected tree, two increment cores in opposite directions were taken using an increment borer at 1.3 m above the ground. Annual ring-widths were measured with an accuracy of 0.01 mm using the LINTAB tree-ring measuring table with the computer program TSAP-Win Scientific Version 0.59 (Rinn 2003).

In Finland, increment cores were collected as part of the 9th (1996 – 2003) and 10th (2004 – 2008) National Forest Inventory (NFI). In the NFI, the total land area is covered by a systematic cluster sample (Tomppo 2006). In this study, plots on sandy soils with relative infertile site (*Vaccinium, Empetrum-Myrtillus,* and *Empetrum-Vaccinium* types (Cajander 1949)), and with infertile site (*Calluna, Myrtillus-Cladina*, and *Cladina* types) were selected. From the north to the south of Finland, five climatically different regions (Sodankylä (SO), Oulun Pohjanmaa (OP), Pohjois-Karjala (PK), Etelä-Pohjanmaa (EP) and Etelä-Karjala (EK) were identified with high density of plots. The number of plots in each region was set to be 100 and the plots closest to the mid-point of each region were included in the sample. In the Finnish NFI, trees to be measured are selected using the angle-gauge method (Bitterlich 1984), except for large trees, which are sampled using a fixed radius. Every seventh tree tallied on temporary sample plots is cored to the pith at 1.3 m height. The tree-ring measuring equipment consists of a microscope connected to a computer. Since 1999, about 50% of cores have been scanned and ring-widths measured using the WinDENDRO™ Software (Regent Instruments Inc., Quebec, Canada). The accuracy of ring-width measurement is 0.01 mm. In this study, only trees with at least 30 annual rings were included.

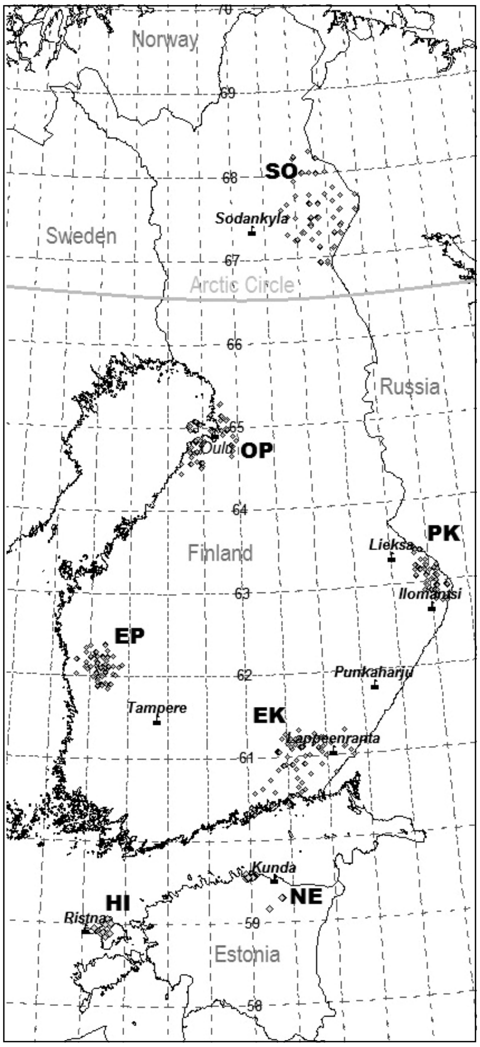

Figure 1. Location of the sample plots and weather stations in Estonia (Hiiumaa Island (HI) and North-East Estonia (NE)) and Finland (Sodankylä (SO), Oulun Pohjanmaa (OP), Pohjois-Karjala (PK), Etelä-Pohjanmaa (EP) and Etelä-Karjala (EK))

A total of 1,024 trees were measured in 551 sample plots (Table 1). Five trees were excluded from the final analysis because they could not be cross-dated. The distribution of sample tree age by regions is shown in Figure 2.

Table 1. Sample sizes and the final number of trees in the analysis

Region	Sample size		Data in analysis
	Plots	Trees	Trees
HI	16	120	120
NE	35	263	263
EK	100	131	131
EP	100	121	120
PK	100	128	128
OP	100	141	138
SO	100	125	124

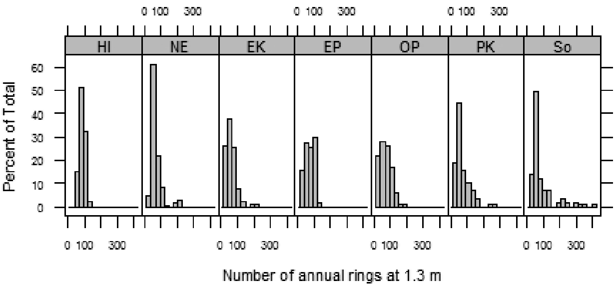

Figure 2. Distribution of tree age at breast height by regions

Growth variation

The tree-ring measurements were visually cross-dated (Pilcher 1990) and assessed using the program COFECHA (Grissino-Mayer 2001, Holmes 1983). Statistical parameters like mean sensitivity (MS), standard deviation (SD), first-order autocorrelation (AR), signal-to-noise ratio (SNR), and *Gleichläufigkeit* (Glk) were calculated to characterise the variations in the tree-ring data. MS is the mean percentage change from each measured annual ring-width to the next (Douglass 1936) and, compared to SD, MS is a measure of the variation at high-frequency (Fritts 1976). AR was calculated to estimate serial correlation (Fritts 1976). SNR represents the strength of the observed common signal among trees (Cook et al. 1990): $SNR = \frac{N\bar{r}}{(1-\bar{r})}$, where $\bar{r}$ is the average correlation between trees and N is the number of trees in the ensemble of standardized tree-ring indices. Glk, a measure of the year-to-year agreement, calculated as the number of times that two series show the same upward or downward trend relative to the previous year (García González and Eckstein 2003); values of Glk greater than 60% were considered significant.

The measured tree-ring series were detrended (by two methods: negative exponent curve and regional growth curve) using the program ARSTAN v6.05P (Cook 1985). Standardization of the regional growth curve (RGC) process was based on double-detrending. First, a negative exponential or linear regression was fit to individual series. Second, a spline curve with 50% cut-off in 67% of n years was fitted. Thereafter, annual indices were calculated as ratios between the measured and fitted values. In the climate-growth analysis, two different standardization procedures were compared, i.e. the EXP series calculated as ratios after the first step described above, and the so-called RGC series (regional growth curve standardization) calculated after the second step. Finally, the indices were pre-whitened using an autoregressive model (ARMA) selected on the basis of the minimum AIC (Akaike 1974) criterion. The regional level chronologies were calculated from single tree index series as average series for each region.

Weather data

Statistical characteristics of weather data, such as annual sums of precipitation (mm) and annual minimum, mean and maximum temperatures (°C) (Table 2) were obtained from the weather stations of the Estonian Meteorological and Hydrological Institute (EMHI) and Finnish Meteorological Institute (FMI).

Table 2. Characteristics of the meteorological stations over the period 1960-2005 (calculated from daily data temperatures T°C and precipitation mm) used in this study

Stations	Region	Latitute N	Longitute E	Elevation m	Min T °C in 1960-1985	Avg Ann. Mean T °C	Max T °C in 1960-2005	Avg Ann. Daily sum of T °C	Avg Ann. sum of prec mm
Kunda	NE	59.31	26.32	2	-33.1	7.4	45.8	2245.2	482.2
Ristna	HI	58.55	22.04	7	-28.4	8.2	31.5	2489.3	476.0
Tampere Härmälä	EP	61.28	23.44	84	-37.0	6.4	32.2	1934.8	477.9
Tampere Pirkkala		61.25	23.37	119	-35.8	6.7	32.2	2033.8	509.0
Lappeenranta airport	EK	61.02	28.09	106	-36.8	6.7	33.1	1968.1	521.3
Punkaharju		61.48	29.19	78	-40.2	6.1	31.6	1845.7	496.7
Lieksa, Lampela	PK	63.19	30.02	98	-40.8	4.9	32.1	1504.4	535.1
Ilomantsi, kirkonkyla		62.41	30.57	162	-39.8	4.8	32.0	1426.6	551.9
Oulun airport	OP	64.55	25.21	14	-41.5	5.0	32.8	1531.2	398.5
Sodankylä	SO	67.21	26.37	179	-49.5	2.4	31.3	721.8	450.9

The data from the closest weather stations to the plot were used and the data from the next to the closest weather station were used to fill gaps in data set. Two types of weather variables, derived from monthly and daily data, were used. Daily weather data were available over the period of 1960 to 2005. Additional mean and sum of weather variables were calculated from daily data and used in the weather-growth analysis (Table 3). Annual values were calculated for the variables drought period (Pn0), annual precipitation sum (Ps10), etc in Table 3. In addition to monthly values, half-monthly values were calculated (from dates

Table 3. Description of weather variables used in this study

Parameters	Desciptions
t_8 ... t_12	previous year monthly mean temperatures from August to December
t1 ... t8	current year monthly mean tempertures from January to August
p_8 ... p_12	previous year monthly sum of precipitation from August to December
p1 ... p8	current year monthly sum of precipitation from January to August
Tsveg	temperature sum of vegetation period (from May to August)
Tmveg	temperatures mean of vegetation period (from May to August)
Tm	mean temperature (°C)
Tsum	annual temperature sum (threshold value 0°C)
t_8w1,w2...t8w1,w2	half-monthly mean temperature from previous to current year August; from dates 1-15 as week 1 (w1) and 16-31 as week 2 (w2)
p_8w1,w2...p8w1,w2	half-monthly precipitation sum from previous to current year August; from dates 1-15 as week 1 (w1) and 16-31 as week 2 (w2)
t_8p1,p2,p3...t8p1,p2,p3	ten day monthly mean temperature from previous to current year August; from dates 1-10 as period 1 (p1), 11-20 as period 2 (p2), 21-31 as period 3 (p3)
p_8p1,p2,p3...p8p1,p2,p3	half-monthly precipitation sum from previous to current year August; from dates 1-10 as period 1 (p1), 11-20 as period 2 (p2), 21-31 as period 3 (p3)
Psum	annual precipitation sum
Psveg	precipitation sum of vegetation period (from May to August)
Pn0	drought period, number of days without precipitation
Ps10	annual precipitation sum, while precip. ≥10 mm
Pn10	length of high precipitation period
Ts0	temperature sum, while temp.<0°C
Tn0	length of frost period, while temp.<0°C
Ts_5 ... Ts_20	temperature sum, while temp.≤-5°C; -10°C; -20°C
Tn_5 ... Tn_20	length of frost period, while temp.≤-5°C; -10°C; -20°C
Ts5 ... Ts25	temperature sum, while temp.≥+5°C; +20°C; +25°C
Tn5	length of vegetation period, while temp.≥ +5°C
Tm5	mean temperature of vegetation period, while temp.≥+5°C
Ts5a	temperatures sum I part of veg.period (May-June), while temp.≥+5°C
Tn5a	length of I veg.period (May-Jun), while temp.≥+5°C
Tm5a	mean temperature of I part veg.per (May-June), while temp≥+5°C
Ts5b	temperature sum II part of veg.per (Jul-Aug), while temp.≥+5°C
Tm5b	mean temperature of II part of veg.per (May-June), while temp.≥+5°C
Tn5b	length of II part of veg.per (Jul-Aug), while temp.≥+5°C
+	positive strong pointer year
++	positive extreme pointer year
-	negative strong pointer year
--	negative extreme pointer year

1-15 as week 1 (w1) and 16-31 as week 2 (w2)) as well as ten day means/sums (from dates 1-10 as period 1 (p1), 11-20 as period 2 (p2) and 21-31 as period 3 (p3)) for temperature and precipitation, respectively.

Estonia has a temperate climate with warm summers and severe winters. The average annual temperature is around 4-6°C (EMHI 2010) and warmer near coastal areas, about 7-8°C (Table 2). The annual precipitation sum is between 500 mm and 750 mm, of which about 40-80 mm falls as snow. The vegetation period (daily air temperature above 5°C) usually lasts from 170 to 180 days (EMHI 2010).

The main factor influencing Finland's climate is the location between the 60th and 70th northern latitudes in the Eurasian continent's coastal zone. The mean annual temperature is about 5.5°C in south-western Finland, decreasing towards the northeast (Table 2). The 0°C mean annual temperature runs slightly to the south of the Arctic Circle. The annual variation in precipitation is rather similar throughout the country. In southern and central Finland, the mean annual precipitation is between 600 and 700 mm, except on the coast where the annual precipitation is slightly lower. In northern Finland, where about half of the rain falls as snow, the annual precipitation is about 600 mm. The lowest annual precipitation has been 200 to 300 mm. In northern Finland, the highest annual precipitation has been around 700 mm, and 900 to 1100 mm elsewhere. The average length of the growing season is 180 days in the south-western archipelago, 140 to 175 days elsewhere in southern and central Finland, and 100 to 140 days in Lapland (FMI 2010).

Correlation analysis

In this study, the chronology length of 46 years (1960-2005) was chosen to assess the influence of weather variables on tree growth by using the Pearson correlation coefficient. The weather variables over an interval starting from August of the previous growth year and ending in August of the current growth year were used in the correlation analysis. The Pearson correlation coefficient was used to evaluate the variations increment indices in each region using the RGC and EXP chronologies. The correlations were considered significant when the correlation coefficient was above 0.3 or below -0.3 ($p < 0.05$). The statistical analyses were done with the SAS (Statistical Analysis System) software (SAS 1996) and freeware R (R-project 2010).

Pointer years

The pointer year analysis is a method of showing annual growth reactions due to abrupt changes in environmental conditions (Cropper 1979, Neuwirth et al. 2007, Schweingruber 1990). We used Cropper (1979) method, where ratios among the raw annual measurements for single trees and their 13-year moving average were calculated as follows:

$$Z_i = \frac{x_i - mean[window]}{stdev[window]}$$

where x_i – tree-ring width in the year i; *mean*[*window*] and *stdev*[*window*] – arithmetic mean and standard deviation of ring widths in the moving window x_{i-6}, x_{i-5}, x_{i-4}, x_{i-3}, x_{i-2}, x_{i-1}, x_i, x_{i+1}, x_{i+2}, x_{i+3}, x_{i+4}, x_{i+5}, x_{i+6}. Years with Z_i higher than 1 or lower than -1 were defined as positive or negative pointer years, respectively (Neuwirth et al. 2007, Pourtahmasi et al. 2007). The positive and negative Cropper values were divided into three classes by intensity: 'weak' for $|Z_i| > 1$, 'strong' for $|Z_i| > 1.28$, and 'extreme' for $|Z_i| > 1.645$ (Neuwirth et al. 2007). Years were considered as common pointer ones for a given chronology if half of the cores displayed pointer values above or below the selected threshold (Panayotov et al. 2010, Schweingruber 1990).

Results

Tree ring chronologies

The mean tree-ring width ranged from 0.985 to 1.453 mm, increasing from the northernmost region to the south (Table 4), except in the NE region. The average standard deviation of the individual ring-width series (before detrending) decreased from the southernmost region to the north. In contrast, the average mean sensitivity was relatively similar in all regions and Glk ranged from 61.893 to 84.944%, which indicate to the significant concordance between trees in regions. The high first-order autocorrelations (AR(1)) reflect a high persistence of the ring-width chronologies, indicating a significant impact of previous year's climate and current year's ring width (Fritts 1976, Fan et al. 2009). Accordingly, AR(1) was high in raw ring-width series. The two chronologies (RGC and EXP) from seven regions in Estonia and Finland (Table 4, Figure 3) were created and compared. The RGC and EXP chronologies showed similar MS and SD values. Between the regions, SNR varied from 6.41 to 26.44 and from 7.27 to 25.2 in the RGC and EXP chronologies, respectively.

The 46-year standardized chronologies ranging from 1960 to 2005, developed by two types of detrending methods, the regional growth curve (RGC) and the negative exponent curve (EXP) are presented in Figure 3, respectively. Correlation coefficients with 95% confidence limits between the methods in regions in

Table 4. Descriptive statistics of raw ring-width series and RGC and EXP chronologies: EK – Etelä-Karjala, EP – Etelä-Pohjanmaa, PK – Pohjois-Karjala, OP – Oulun Pohjanmaa, SO – Sodankylä, HI – Hiiumaa Island and NE – North-East Estonia

	EK	*EP*	*OP*	*PK*	*SO*	*HI*	*NE*
Measurements							
Period	1792-2007	1854-2007	1822-2007	1741-2007	1597-2007	1872-2007	1787-2007
Length of chronology (years)	215	153	185	266	410	135	220
Mean tree-ring width, mm (raw series)	1.308	1.197	1.176	1.179	0.985	1.453	1.152
Standard deviation (SD)	0.388	0.334	0.429	0.335	0.291	0.549	0.431
Mean sensitivity (MS)	0.146	0.139	0.138	0.127	0.136	0.140	0.143
Mean first-order autocorrelation (AR(1))	0.778	0.789	0.769	0.826	0.815	0.824	0.841
Gleichläufigkeit (Glk), %	61.893	75.463	70.283	71.315	84.944	80.125	72.643
Standardized chronology (EXP)							
Mean index	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Standard deviation (SD)	0.201	0.135	0.131	0.120	0.130	0.140	0.141
Mean sensitivity (MS)	0.163	0.154	0.141	0.133	0.146	0.154	0.168
Mean correlation between trees	0.541	0.689	0.759	0.671	0.728	0.476	0.564
Mean first-order autocorrelation (AR(1))	0.136	-0.005	0.005	-0.017	-0.116	-0.129	-0.004
Signal-to-noise ratio (SNR)	9.43	17.72	25.20	16.32	21.41	7.27	10.35
Standardized chronology (RGC)							
Mean index	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Standard deviation (SD)	0.126	0.128	0.149	0.107	0.125	0.114	0.149
Mean sensitivity (MS)	0.142	0.149	0.147	0.119	0.132	0.141	0.173
Mean correlation between trees	0.766	0.747	0.768	0.660	0.753	0.445	0.789
Mean first-order autocorrelation (AR(1))	-0.130	0.039	-0.050	0.013	-0.101	-0.159	-0.037
Signal-to-noise ratio (SNR)	26.19	23.62	26.48	15.53	24.39	6.41	29.91

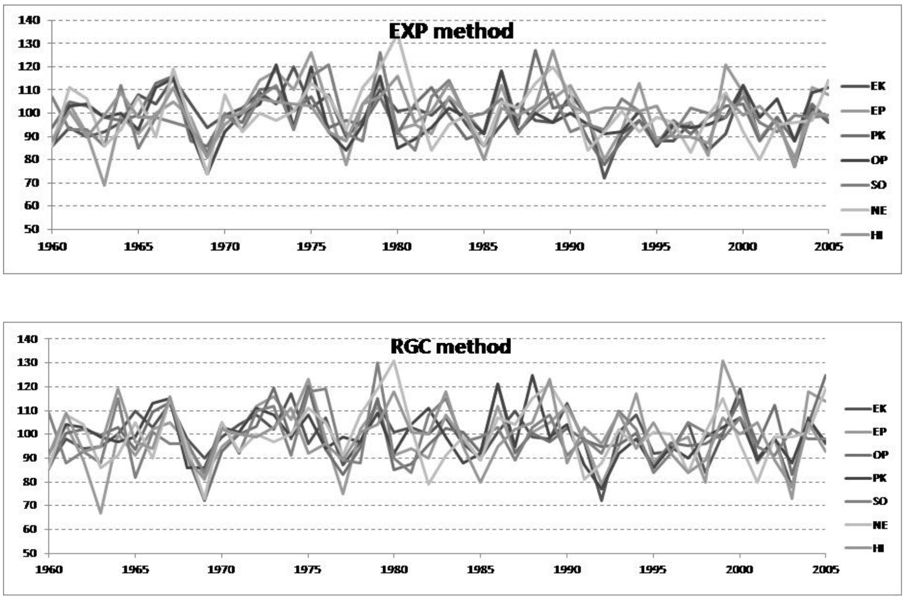

Figure 3. Standardized chronologies of Scots pine in different regions in Estonia and Finland

the radial growth variation from 1960 to 2005 are shown in Table 5. The highest correlation was found in Finland (PK region), r = 0.983, similar results in SO, EP and NE. These results indicate a significantly high correlation between two detrending methods in regions. However, as the results of compared methods were close to each other, only the results of the RGC method are presented in further analysis.

Table 5. Correlation matrix between the RGC and EXP chronologies in each region

Regions	EK	EP	OP	PK	SO	HI	NE
Correl. coef.	0.917	0.981	0.963	0.983	0.982	0.868	0.975
Lower limit	0.853	0.965	0.933	0.969	0.967	0.771	0.955
Upper limit	0.955	0.991	0.981	0.992	0.991	0.927	0.987

The correlation coefficients between the index series of analyzed regions in Finland and Estonia are presented in Table 6. No significant correlations were found between the chronologies in Sodankylä, located in northern Finland, and the southern study sites (regions). Indexes on the Hiiumaa Island (HI), located on the west coast of Estonia and in the eastern part of the Baltic Sea, significantly correlated with the chronologies in southern regions (EK and EP) in Finland and north-east of Estonia, respectively. The results show significant correlation between growth variations in closely located regions (Figure 4).

Table 6. Correlation matrix between the regions based on the RGC chronologies. * significance at 0.05 level

Regions	EK	EP	OP	PK	SO	NE
EK						
EP	0.615*					
OP	0.405*	0.675*				
PK	0.497*	0.492*	0.585*			
SO	0.196	0.396*	0.425*	0.285		
NE	0.292*	0.429*	0.327*	0.368*	0.086	
HI	0.396*	0.326*	0.173	0.226	0.169	0.395*

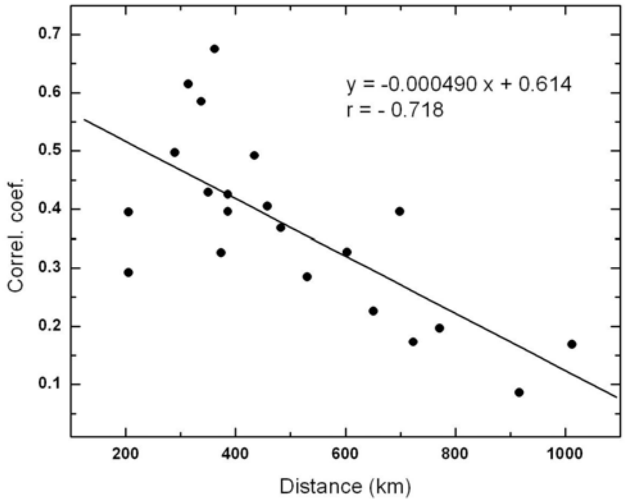

Figure 4. Spatial synchrony of dendrochronological data. Correlations between the chronologies decline as a function of geographical distance. This is indicated by the negative slope of the trend line and quantified further by Pearson correlation (r). Equations quantify the linear dependence between correlativity (y) and distance (x)

Weather-growth relationship

Monthly weather data

Negative correlation was found between increment indices and the temperature in August of the previous year (t_8) in regions HI, EK, PK, and positive correlation in region SO (Table 7). The temperature in September of the previous year (t_9) had positive correlation in OP, while the temperature in December (t_12) had negative correlation in NE. Temperature in March of the current year (t3) correlated positively in EP and SO, as well as temperature in April (t4) in EP. In SO, the temperature in July of the current year (t7) had positive correlation, and the temperature in August (t8) had negative correlation in HI. In EP and OP, the annual temperature sum (Tsum) also had positive correlation, while in SO, positive correlation was also found between the temperature sum (Tsveg) and mean temperatures (Tmveg) during the vegetation period (from May to August).

In different regions, the sum of precipitation had positive correlation in August (p_8) and December of the previous year (p_12), as well as in March (p3), May (p5) and August of the current year (p8) (Table 7, Figure 5). Furthermore, the precipitation sum during the whole growing season (Psveg) had positive correlation in HI. Negative correlation was only found with the precipitation sum in April of the current year (p4) in EK.

Weather variables for two-week periods

However, it is possible to use daily weather data to get more information about the effects between specific climate periods and increment indices. Figure 6 shows the results of the analysis between mean temperatures and indices, respectively for each month for the first (w1 – from1-15 day) and the second half (w2 – from 16-31 day) (Table 3). Also, correlation between indices and the precipitation sum was estimated for two week periods, illustrated in Figure 7 and presented in Table 7. Positive correlation was found between indices and the temperature in the second part of September of the previous year (t_9w2) in OP. Temperature at the beginning of December (t_12w1) of the previous year had negative correlation in HI, while positive correlation in the same region occurred with the temperature in the beginning of January of the current year (t1w1). Temperatures at the end of March of the current year (t3w2) and at the beginning of April (t4w1) had positive correlation in EP and HI, respectively. Positive correlation was also found between the temperature at the beginning of May (t5w1) and increment indices in SO. Temperature in the second half of June (t6w2) had positive correlation in EP, PK and NE. In SO, temperature at the beginning of July (t7w1) also had positive correlation with growth indexes.

Table 7. Results of correlation analysis between RGC method and weather variables. Threshold value for correlation coefficient 0.3

	Regions						
Parameters	HI	NE	EK	EP	OP	PK	So
	Temperature						
t_8	neg		neg			neg	pos
t_8w1					pos		
t_9					pos		
t_9p2		pos			pos		
t_12		neg					
t_12w1		neg					
t_12p3	pos						
t1w1	pos						
t1p1	pos						
t3				pos			pos
t3w2				pos			
t3p3				pos			pos
t4				pos			
t4w1	pos			pos			
t4p1				pos	pos		
t5w1							pos
t5p1							pos
t6w2		pos		pos		pos	
t6p1		pos					
t6p3				pos		pos	
t7							pos
t7w1							pos
t7p2							pos
t8	neg						
t8p3	neg						
Tsveg							pos
Tmveg							pos
Tsum				pos	pos		
Ts0	pos						
Ts_5	pos			pos			
Tn_5	neg						
Tn_10	neg						
Ts25	neg						
Ts20	neg						
Tn5			neg				
Tn5a			neg				
Tm5a		pos					
	HI	NE	EK	EP	OP	PK	SO
	Precipitation						
p_8	pos	pos		pos	pos	pos	
p_8w1		pos		pos	pos		
p_8p2	pos						
p 8p3						pos	

The estimated correlations between the increment indices and precipitation sum in two-week periods are given in Figure 7 (Table 7). In EP, OP and NE, precip-

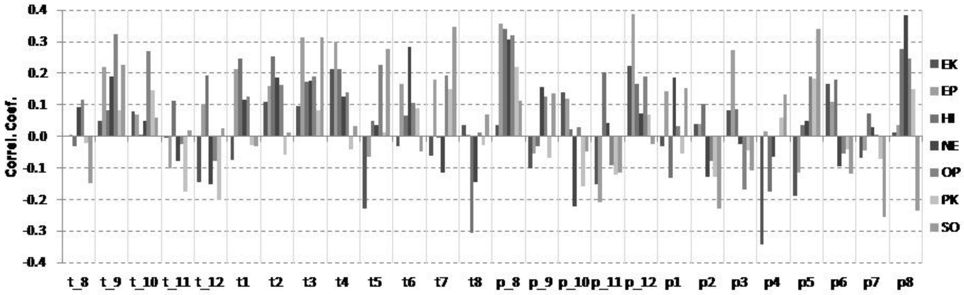

Figure 5. Correlation coefficient between monthly weather variables (from previous year August to current year August) and standardized series

a

b

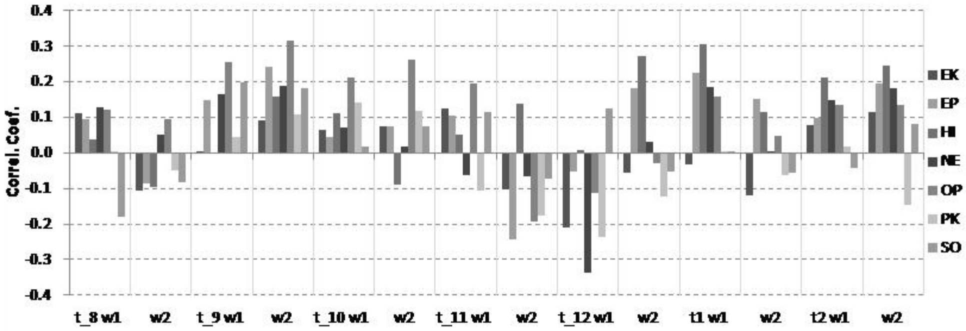

Figure 6. Correlations between the mean temperature (w1 – dates 1-15 and w2 – dates 16-31) and increment indices in two-week periods

a

b

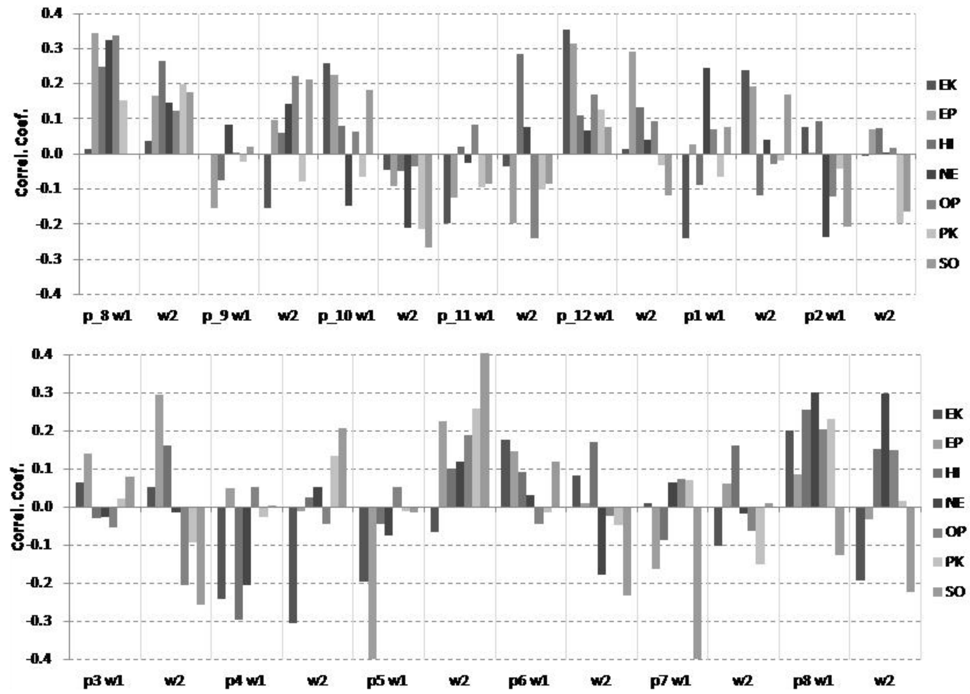

Figure 7. Correlations between the precipitation sums (w1 – dates 1-15 and w2 – dates 16-31) and increment indices in two-week periods

itation at the beginning of August of the previous year (p_8w1) had positive correlation. Positive correlation was also found between the indices and precipitation sum at the beginning of December of the previous year (p_12w1) in EK and EP. In EK, the precipitation sum at the end of April (p4w2) had negative correlation, also the precipitation at the beginning of May (p5w1) in EP, while in SO, precipitation at the end of May (p5w2) had positive correlation. During the growing season, precipitation at the beginning of July (p7w1) had negative correlation in SO. Positive correlation was found between precipitation at the beginning and end of August (p8w1, w2) in NE.

Weather variables for ten-day periods

Positive correlation was detected between increment indices and temperature in the middle of September (t_9p2) in NE and OP (Figure 8). In HI, temperature at the end of December of the previous year (t_12p3) and at the beginning of January (t1p1) had positive correlation with growth indexes. Temperature at the end of March (t3p3) and the beginning of April (t4p1) had positive correlation in (EP, SO) and (EK, EP, OP, HI,) respectively. In SO, temperature at the beginning of May (t5p1) had positive correlation. Positive correlation was found in NE in temperature in the beginning of June (t6p1), also at the end of the same month (t6p3) in EP and PK. Positive correlation was found between indices and temperature in the middle of July (t7p2) in SO. In HI, temperature at the end of August of the current year (t8p3) had negative correlation with the radial growth.

In HI and PK, positive correlation occurred between the precipitation in August of the previous year, in the middle and at the end of the month (p_8p2, p3), respectively (Figure 9). Negative correlation was found between indices and precipitation in the middle of October of the prior year (p_10p2) in NE. Precipitation in the middle of December of the previous year (p_12p2) had positive correlation in EK, EP and HI. At the end of March (p3p3) precipitation had positive correlation in EP, while had negative correlation in the mid of April (p4p2) in EK and positive correlation in SO. At the beginning of May (p5p1) negative correlation between growth indices and precipitation in EP was found, while positive correlation was found at the end of the same month (p5p3) in EP, PK, and SO. SO had negative correlation between indices and precipitation at the beginning of July (p7p1). Positive correlation was found between increment indices and precipitation at the beginning of August (p8p1) in HI and NE and also at the end of the month (p8p3) in NE.

Periods with extreme weather conditions

Significant correlation was found between the weather variables listed in Table 3 and radial growth indices in this study (Figure 10; Table 7). The annual temperature sum (Tsum) correlated positively in regions EP and OP. In HI, positive correlation occurred with several weather variables, like the precipitation sum on vegetation period (Psveg), annual precipitation sum (Psum), annual precipitation sum of high rainfall and length (Ps10 and Pn10 respectively) and the annual temperature sum below 0°C or -5°C (Ts0 and

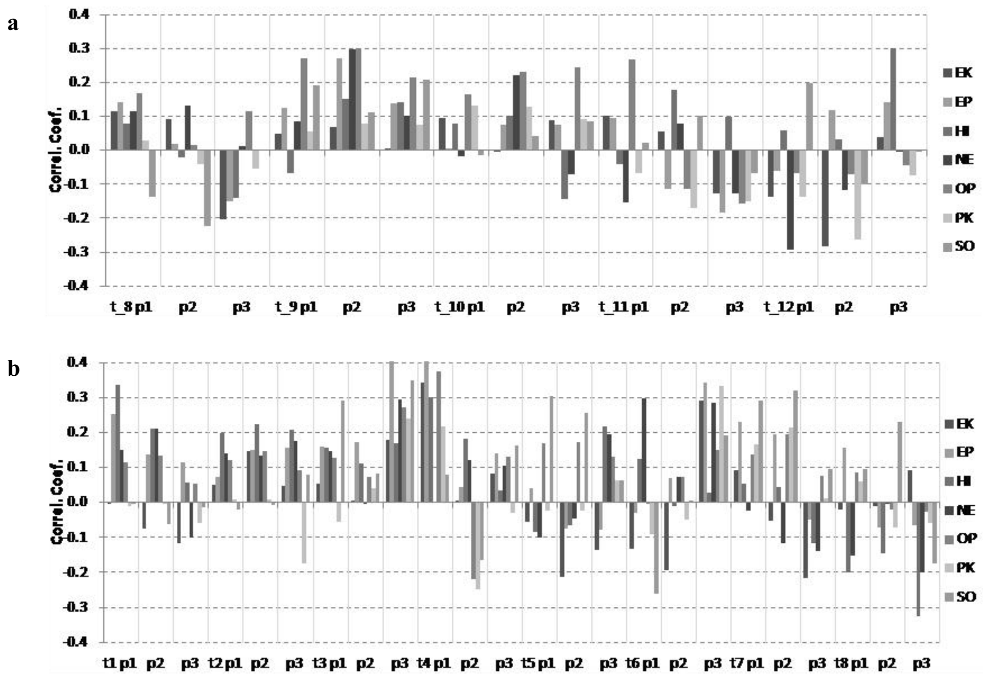

Figure 8. Correlations between the mean temperatures (p1 - dates 1-10, p2 - dates 11-20 and p3 - dates 21-31) and radial growth indices in ten-day periods

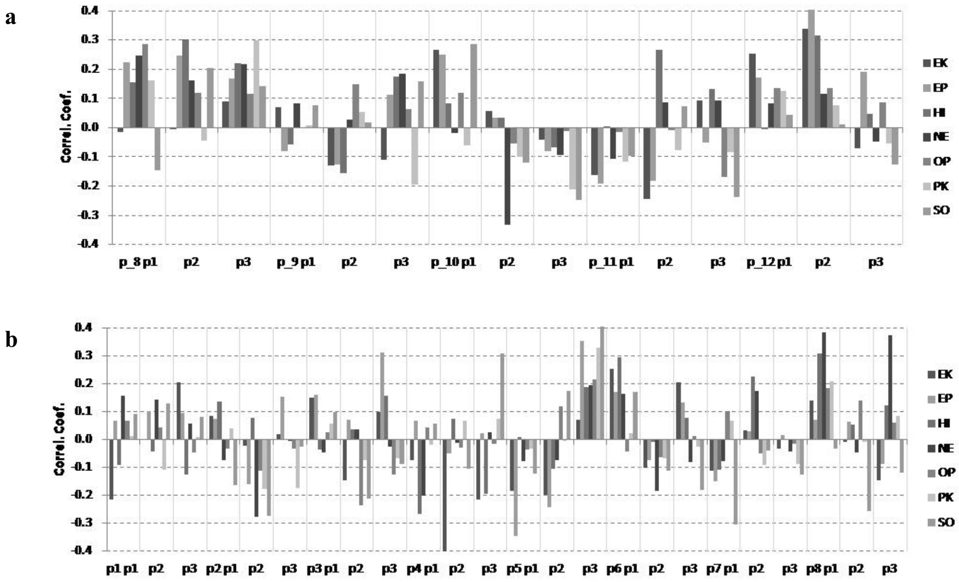

Figure 9. Correlations between ten-day period precipitation sums (p1 - dates 1-10, p2 - dates 11-20 and p3 - dates 21-31) and increment indices

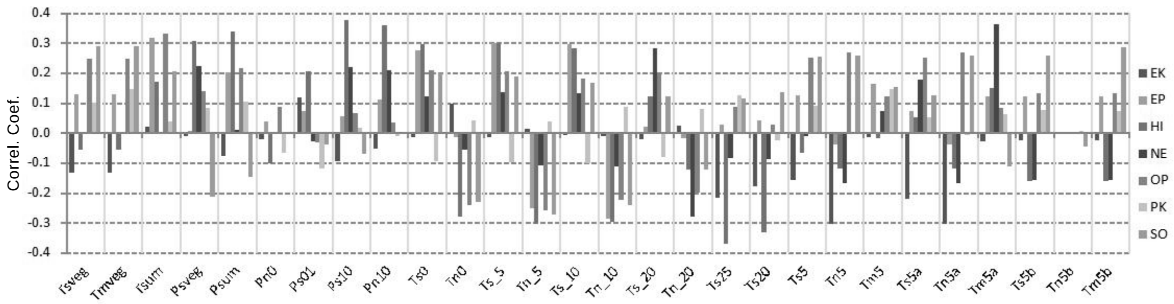

Figure 10. Correlations between several weather variables and increment indices

Ts_5 respectively). Temperature (length of frost period below -5°C (Tn_5) or -10°C (Tn_10), also annual temperature sum over +20°C (Ts20) or +25°C (Ts25)) had negative correlation in HI. In NE positive correlation was found between mean temperatures of the first part of the vegetation period (Tm5a) and increment indices. The length of vegetation period (Tn5, Tn5a) correlated negatively in EK. These results indicate that precipitation had a positive effect on growth in southern regions and also that temperature is limiting tree growth in southern regions.

Pointer year analysis

Strong and extreme pointer years were identified from different regions in Finland and Estonia (Table 8). In Finland, significant negative pointer years 1992 (--) and 2003 in EK were detected and 1967 (++) and 1990 were positive years; in EP, negative pointer years were 1963 (--) and 2003 (--), while positive event years were 1975 (++) and 1990; in OP considerably positive pointer years were 1967 and 1975 (++); the significant positive pointer years were 1967 (++), 1975 and 1988 (++) in PK; in SO, the negative event year was 1981 and the positive year 1976 (++). In Estonia, the significant negative event year was detected to be 2003 in HI, and positive years were 1967 and 1980; in NE, important positive years were 1967 (++), 1980/1981 (++), 1989/1990 (++). The pointer year analysis identified a total of 11 extreme event years. A relevant positive pointer year 1967 was detected in EK, OP, PK, HI and NE, while the negative pointer year was 2003 in EK, EP and HI. The results of pointer year analysis indicate the different weather variables which have the essential effect on the sharp decrease or increase in the radial growth of pine trees for the studied period (1960-2005).

Discussion

In this study we explored the spatial correlation between index series and between climatic factors and

Table 8. Pointer years in different regions; positive (++) extreme and (+) strong years, negative (--) extreme and (-) strong years, respectively

Year	*EK*	*EP*	*OP*	*PK*	*SO*	*HI*	*NE*	*Comments*
1963		- -						EP: low annual temperature sum Tsum=1286°C
1967	+ +		+	+ +		+	+ +	EK: growing season started in the middle of May t5=+7.6°C; OP: vegeation period started in middle of May t5=+6°C; HI: mild winter (t_12...t2) Tm=-2.9°C, high amount of precipitation during growing season Psveg=264.8 mm; NE: no significant weather event recorded in this year
1975		+ +	+ +	+				EP: mild winter (t_12...t2) Tm=-3.03°C, growing season started in the end of April t4=+5.1°C; OP: mild winter (t_12...t2) Tm=-3.9°C and vegetation period started in the beginning of May t5=+8.1°C; PK: annual daily Tsum=1841.8°C and rainy previous year August p_8=145 mm
1976					+ +			SO: no extrem weather events recorded in this year
1980						+	+ +	HI: no extrem weather events recorded in this year; NE: warm winter, vegetation period started in the end of April t4=+6.8°C
1981					-		+ +	SO: high amount of preciptiation during growing season Psveg=290.5 mm; NE: warm winter, growing season started in the beginning of May t5=+5.9°C
1988				+ +				PK: previous year August was rainy p_8=140 mm
1989							+ +	NE: warm winter (t_12...t2) prior the growing season Tm=-0.4°C, vegetation period started in mid April t4=+7.5°C
1990	+	+					+ +	EK: high annual temperature 1989/90, growing season started early in April t4=+5.3°C; EP: no extrem weather events in this year; NE: warmer winter (t_12...t2) prior the growing season Tm=-0.9°C, vegetation period started in the end of April t4=+7.6°C
1992	- -							EK: no weather extremes recorded for this year
2003	-	- -				-		EK: beginning of January was very cold t1=-24.7°C; EP: dry and hot previous year August t_8=+17.7°C, p_8=28.7mm; HI: previous year dry and hot summer affected in this year the radial growth of trees

the diameter increment of Scots pine (*Pinus sylvestris* L.) growing on dry and sandy site types in different regions in Finland and Estonia. The chronologies generally display a high year-to-year variability (mean sensitivity), which is typical of conifers growing in dry environments. A similar climate impact to the radial growth in mean temperature and the sum of precipitation in August of the previous year was found in several regions (HI, EK, OP, PK), which means that drought could be the main growth limiting factor in several regions. Weather parameters from January till April were more important in the south compared to the north, where the summer (July) was significant. The correlations between spring temperatures (mid-March – early-April) and radial increment seem also to be positive in some regions. This relationship is interesting and it has been reported in some early Nordic studies (e.g. Laitakari 1920, Holmsgaard 1955, Jonsson 1969). Also the recent study by Holopainen et al. (2006) found that the correlation between spring temperatures and tree-rings occur, at least in southern Finland, and was strongest at the end of the 1800s and beginning of the 1900s.

Generally, the negative effect of the temperature of the previous year on the radial growth could be explained by the promotion of bud differentiation during this time. The late summer temperature affects the amount of nutrient storage which encourages sprouting in spring. This in turn affects the next growing year ratio of sprouts and diameter increment (Lõhmus 1992). A similar effect is mentioned in Finland by Henttonen (1984) and in Sweden by Jonsson (1969). Additionally, the reason for that could be regional diversity, length of the growing season, growing conditions, winter severity and longevity etc. Considering that a higher temperature would stimulate tree growth in spring, severe and long winters have a limiting effect on tree growth. Usually, temperature may be considered as the most important single factor initiating growth activity (Vaganov et al. 2006); however, low humidity can cause an earlier termination of the growth in a season (Fritts 1976). A combination of temperature and humidity changes in particular intervals of a season produces acceleration or deceleration of growth processes (Schweingruber 1996). It is confirmed by Jaagus (2006) and Jaagus et al. (2003) that beside temperature, precipitation has the most profound effect on growth; however, precipitation is an extremely unstable climate variable which makes long-term changes almost impossible to predict.

Previous studies on growth variation in northernmost Fennoscandia have concentrated on Scots pine (Elfving et al. 1996, Mäkinen et al. 2002) and showed that the average temperature in July is the best climatic predictor of the radial growth, followed by the temperatures in August and June. This study presents a geographical approach to the growth variation of Scots pine and the relationships between the radial growth and weather. The results of previous studies indicate that in Finland, the growth variation of Scots pine is related to the temperatures of the current summer, even though the dependence in not very strong in the southern part of Finland (Mäkinen et al. 2001, Mikola 1950). One of the expected effects of climate change is an increase in temperatures. Warmer temperatures may increase tree growth in northern Europe, but these types of effects are unlikely in central Europe. Temperatures during the growing season are the most important for Scots pine growth in dry sites. Notable is the positive and significant influence of precipitation at dry sites prior to the growing season. The observed correlations with weather variables were in most cases rather low. Fritts et al. (1965) concluded that climatic control of the growth increases towards the limits of tree growth, i.e. trees growing on more favourable sites do not respond as strongly to drought as trees on dry sites. Therefore, the relationship between tree growth, climatic conditions, and site characteristics can be very complex and the factors that affect tree growth may even change from year to year. The result may also indicate that air temperature and precipitation influence the chronology characteristic in a different manner. The changes in average temperature and precipitation followed by the possible climate change may not necessarily be the most influential factors regulating tree growth in the future. Possible changes in severity and frequency of extreme stresses may influence growth more (Mäkinen et al. 2002). High winter temperatures may have a negative effect on tree growth due to increasing respiration and evapotranspiration during a period when the losses cannot be replaced by photosynthesis and water supply (Lõhmus 1992, Mäkinen et al. 2000, Traquillini 1979).

Environmental factors influencing tree growth and their temporal variation may naturally be rather different in the seven regions. It is logical to expect a decline in the radial growth and changes in factors controlling tree growth at the northern sites in comparison with the southern ones. There are differences in the timing and duration of the growing season, as well as in climatic conditions, most noticeably from north to south (Briffa et al. 1987, Mäkinen et al. 2002). Going from the north to the south, tree-growth becomes less affected by growing season temperatures and more affected by e.g. precipitation (Lindholm et al. 1997). Therefore, climatic prerequisites for tree growth are expected to change gradually from south to north throughout the temperate and boreal zones (Hofgaard et al. 1999).

The pointer year analysis identified 11 pointer years in different regions. A significant positive pointer year was detected in 1967 (EK, OP, PK, HI and NE), while the negative pointer year was 2003 in three different regions (EK, EP and HI). The main causes for the sharp reduction of the radial growth revealed by pointer year analysis are connected to droughts, winter colds and spring frosts. The depression of the growth is very easily attributed to negative weather events in the period, when the meteorological observations are available. Extreme events usually last only a few months and the organism can survive these conditions (Ahas et al. 2000), but the influence of extreme events may last for several years (Jaagus et al. 2003).

These results of analysis indicate the importance of daily weather variables, which help to detect the effect of a specific period on the radial growth. In general, more detailed climate variables like daily data are more advanced data sets for detailed analysis and finding out the exact length of frost or heat period, also the length of the growing season and other significant variables which are influencing tree increment.

Conclusions

Diverse climate parameters are found in different regions, affecting the radial growth of pine trees. However, the results of analysis indicated to the significant relationship between the diameter increment and mean temperature and the sum of precipitation in August of the previous year and also with early spring temperature (mid-March – early-April). The results of pointer year analysis distinguished 11 extreme pointer years in different regions, the analysis of which revealed the significant response to the winter temperature and the temperature of growing season. As the relationship between tree growth and climatic conditions, also with site characteristics are very complex and the factors that affect tree growth may even change from year to year.

However, in the future, more research would be needed between weather data and growth increment with different species, at more comprehensive sites, in regions and different growing conditions.

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ВАРИАЦИИ ПРИРОСТА СОСНЫ ОБЫКНОВЕННОЙ В ЭСТОНИИ И ФИНЛЯНДИИ

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Резюме

В данной статье представлены результаты дендрохронологических и дендроклиматологических исследований радиального прироста сосны обыкновенной *(Pinus sylvestris* L.) в сухих лесах Эстонии и Финляндии. Сердцевины деревьев для изучения годичных колец были получены из двух регионов в Эстонии, и из пяти регионов в Финляндии. В общей сложности были изучены 1024 дерева на 551 пробном участке. В Эстонии сердцевины были взяты из деревьев, растущих поблизости пробных участков, и с участков национального лесного кадастра в Финляндии. Отношения между двумя типами стандартизированных индексов серии (региональной кривой роста РГК и отрицательным показателем кривой EXP) и метеорологическими параметрами, регистрируемыми ежедневно, были охарактеризованы на основании корреляционного анализа. В зависимости от местоположения, радиальный прирост сосны обыкновенной позитивно коррелирует с количеством осадков, и негативно коррелирует со среднемесячной температурой. Аналогичное влияние климата на радиальный прирост при средней температуре и сумме осадков в августе прошлого года было найдено для нескольких регионов (HI, EK, OP, PK). Таким образом, можно сделать вывод, что засуха является ключевым фактором, ограничивающим прирост. Позитивная корреляции между средней температурной весной (середина марта - начало апреля) и приростом диаметра деревьев была значима в некоторых регионах (HI, EK, EP, OP, SO). Для анализа различных регионов использовался метода Кроппера. Согласно результатам анализа, 1967 и 2000 были наиболее значимыми реперными годами, а 1969 был отрицательным в пяти регионах. Таким образом, погодные условия влияют на рост деревьев с юга на север.

Ключевые слова: корреляционный анализ, кольца прироста, перманентные участки, участки национального лесного кадастра, радиальный прирост, биогеография, метод Кроппера