Changes in the Radial Growth of Two Consecutive Generations of Scots Pine (*Pinus sylvestris* L.) Stands

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Pärn, H. 2012. Changes in the Radial Growth of Two Consecutive Generations of Scots Pine (*Pinus sylvestris* L.) Stands. *Baltic Forestry* 18(1): 12–24.

Abstract

Changes in the radial growth in two consecutive generations of Scots pine stands were investigated. Two study sites from different locations in Estonia were selected for this study. The stands on both study sites were represented by two consecutive generations growing at the same sites and in the same site conditions. The differences in the radial growth of the successive stand generations were assessed using the average tree-ring widths of the same cambial age of stands at ages of 11–30, 11–40 and 11–50 years. Analysis showed that the radial growth of young generations exceeded that of old stands at the same cambial age. These differences decreased with the increasing age of the stands. The growth of the studied young stands may have been positively influenced by the increased N deposition and elevated CO_2 level during the second half of the 20th century. Considering the rising average temperature in the winter months and increasing total precipitation in July during the last century, it may be assumed that long-term climate change may have been a reason of the increasing growth of young generations of pine.

Key words: Scots pine, tree ring, latewood, climate change

Introduction

The potential productivity of a forest site has been regarded as natural and stable in a long-term perspective (Elfing et al. 1996). Environmental changes such as increase of CO_2 in the atmosphere, deposition of pollutants and climate changes since the 1950s have had various effects on the forest ecosystems. The increasing human impact on the environment makes the stability of the site conditions questionable.

The forest inventories carried out at the end of the 20th century in European forests indicate both positive and negative changes in forest growth (Spiecker et al. 1996). In contrast to the research results about forest decline in Central Europe in the 1970s and 1980s, some studies showed that forest growth actually increased in several sites (Eriksson and Johansson 1993).

Analysis of the inventory data, height growth and stem data revealed a greater height growth of the young Norway spruce (*Picea abies* [L.] Karst.) stands when compared to that of present-day old stands at the same age in Eastern Germany with greatest differences between the ages of 40 and 80 years (Wenk et al. 1990, Wenk and Vogel 1996). Also increasing trends in both radial and height growth of Norway spruce and beech (*Fagus sylvatica* L.) were observed in this region (Untheim 1996). A strong positive long-term growth trend of Siberian spruce (*Picea obovata* Ledeb.) in North-West Russia was observed (Lopatin et al. 2007). The rise in the potential productivity of Swedish forests from 3.2 m^3 ha^{-1} in 1920s to 5.2 m^3 ha^{-1} in 1990 means a relative increase of about 60% (Elfing et al. 1996). The average increase of site index H_{50} by 2.1 m for pine stands, 1.6 m for spruce stands and 2.5 m for birch stands from the 1950s to the 1990s was found in Estonian forests (Kiviste 1999). On the other hand, no long-term trend in the radial growth of Scots pine was found in Southern Finland during the last 100 years (Mielikäinen and Timonen 1996). At higher elevations of the German Alps and Middle Mountains, with high influx of air pollution, diminishing height and volume growth were in sharp contrast to improving growth trends in lowlands (Pretzsch 1996).

Tree-ring data are appropriate for detecting factors such as climate fluctuations that influence tree growth. Therefore dendrochronological techniques have been widely used for identifying forest growth trends (Neumann and Schadauer 1995, Badeau et al. 1996, Sinkevich and Lindholm 1996, Lopatin et al. 2007). In some cases the comparison of the radial growth parameters of stands of two consequtive generations has given reliable results (Bert and Becker 1990, Neumann and Schadauer 1995).

Temperature and precipitation are often analysed as influencing factors of growth changes because of the wide availability of these data. As the monthly temperatures and precipitation during the dormant and vegetation periods vary considerably from year to year, scientists are of the opinion that it is better to study the climate–growth relationships using along the whole tree-ring width the widths of the constituents of the annual tree-ring: earlywood and latewood separately (Lebourgeois 2000, Miina 2000). This helps to understand the influence of the climatic variability on the annual diameter increment and on the wood properties inside tree-rings such as early–latewood proportion, lignification of the cell walls and wood density (Gindl et al. 2000, Kilpeläinen et al. 2003). The early- and latewood may have different sensitivity to climate variation. The reliability of the climatic response of early- and latewood, shown by Lebourgeois (2000), suggests that in studies both parameters can be used to obtain subseasonal climatic information.

The aim of this study was to compare the radial growth of consecutive generations of Scots pine stands. The hypothesis was that the present young stands indicate higher growth rates than old stands did at the same age. It is assumed that the consecutive generations were growing at the same site unit in the same site conditions and are of the same genetic composition.

Materials and methods

Study sites

Two study sites were selected for this study. Both sites were represented by two consecutive generations of Scots pine stands growing at the same location and in the same site conditions. The Kõiguste study site (58º22’ N, 22º59’ E) is located on Saaremaa island, the largest of the Estonian islands in the Baltic Sea. The stands are defined as of *Hepatica* site type by local classification of site types (Lõhmus 2004). The age of the old stand was 160 years and that of the young stand was 55 years. The Pirita study site (59º28’ N, 24º52’ E) is located in North Estonia, near Tallinn, the capital of Estonia. The stands at this site are defined as of *Rhodococcum* site type. The age of the old stand was 155 years and that of the young stand, 55 years. All stands are of natural origin. No disturbances and management history are known for any sampled stands.

Sampling and measurements

In all stands, 15–20 dominant or co-dominant trees were sampled for analysis of radial growth. Lack of damage or defect was considered in sample tree selection. Each sample tree was cored at breast height (1.3 m) on the southern and northern sides of the stem using a 4.3 mm increment corer. In laboratory each core, when dry, was mounted onto a grooved holder and the surface of the cores was cleaned and finished using sandpaper. The cores were crossdated with each other by regional pointer years to identify missing or false rings. The widths of the tree rings and latewood part of the rings were measured to the nearest 0.01 mm with the LINTAB tree-ring measuring system. Crossdating quality was assessed using the COFECHA program available in the Dendrochronology Program Library (DPL) version 2.1 (Holmes 1983). The trees with cores that were impossible to crossdate or poorly correlated with others were eliminated from further analysis. Only cores where the innermost rings allowed the estimation of pith location and cambial age were inluded in the analysis.

The estimating of differences in radial growth

The differences in the radial growth of successive stand generations were assessed using the average tree ring widths of the same cambial age of stands at age of 30, 40 and 50 years. The constant cambial age method consists in considering simultaneously, in the whole sample, the tree rings developed at a given cambial age but in various calendar years. The cambial age of a given tree ring is the age of the tree when this tree ring was built (Briffa 1992, Badeau et al. 1996). In the present study, the increment cores were taken at the height of 1.3 m. On the ground of the height measurements of young pines with well-known age, it was detected that pines in the study areas reach this height in ten years. So the tree ring next to the pith at the height of 1.3 m denotes the 11th year in the tree life. As a result, the even cambial age of the tree rings is achieved. It will be considered that the same cambial age of tree rings in different trees may be reached in different calendar years with different climatic conditions. When the age of trees in a stand varies considerably, standardized tree ring indices should be used instead of the natural tree ring widths to eliminate the effect of age trend. The variations in the age of trees in the stands used in the given study were small (5–6 years) and thus the age-caused differences in the radial growth were not large. Therefore, in the growth analysis the natural tree ring widths were used.

Statistical analysis

The tree-ring widths on the northern and southern sides were averaged to obtain a tree-ring width. Then a set of sample statistics including the average tree-ring width and average latewood width, average percentage of latewood, variance, mean sensitivity in tree ring time series and similarity of the radial growth between stands were computed for each stand. Mean sensitivity measures the relative difference in tree-ring width from one ring to the next reflecting the effect of limiting environmental factors on growth. The values of mean sensitivity range between zero where there are no differences between adjacent ring widths, and two, when a zero value (missing tree-ring) occurs next to a nonzero one in the tree-ring width series (Fritts 1976). Similarity of the radial growth between stands was assessed by synchronity Cx, which can be calculated as

$$Cx = \frac{n^{+} \cdot 100}{n-1},$$

where n^{+} is the number of yearly intervals coinciding in trends of tree-ring width variation (increasing or decreasing) between two adjacent years in tree-ring width series compared and n is the length of tree-ring series (Битвинскас 1974). The lengths of series have to be equal and the variation in tree-ring widths in the same calendar years should be compared. The synchronity value of 100% indicates coinciding ring-width variation trends between adjacent tree rings in corresponding years in the ring-width series compared.

For estimating the relationships between climate factors and the radial growth of trees the tree-ring and latewood widths were standardised. Version 6.04P of the ARSTAN program (Cook et al. 1997) in DPL was used for standardisation. On the ground of the visual examination of the growth, curves of stands the series of raw ring data of Pirita stands were detrended with 67% *n* spline and these of the Kõiguste stands with the negative exponential curve or linear regression line. The ARSTAN versions of master chronologies were used in further analyses. The latewood width series of the stands were standardised using 67% *n* splines. Some basic chronology statistics such as mean sensitivity, first order autocorrelation, mean correlation between trees, expressed population signal (EPS) and signal-to-noise ratio (Briffa and Jones 1990; Wigley et al. 1984) were calculated for each tree-ring and latewood series.

For estimating the relationships between the climate and the radial growth of trees correlation analysis was applied using software DENDROCLIM2002 (Biondi and Waikul 2004). The climate–growth relationships were studied during the whole life period of stands. The starting year (1921) of the analysis of the Kõiguste old stand was determined by the availability of the climate data. Relationships between climate and the tree growth were estimated comparing the site index chronologies with mean monthly temperatures and total precipitation from the previous June to the current July. The climate data of the previous year were included in the analysis because the climate of the preceding growth session influences the tree growth in the current year (Fritts 1976). To study the age-dependent climate sensitivity correlations between tree-ring width and average monthly temperatures were calculated at different ages with the step of 20 years in the case of the old generations of the stands.

The statistical significance of differences in the average tree-ring widths, average latewood widths and average percentage of latewood between stands was tested by two-tail Student's test. The *t*-tests were considered significant at $p < 0.05$.

Climate data

The monthly average temperatures and monthly total precipitation data were collected from the two nearest to the selected study sites meteorological stations, Vilsandi (58º22'59" N; 21º48'55" E) and Tallinn-Harku (59º23'54" N; 24º36'15" E) of the Estonian Meteorological and Hydrological Institute. The Vilsandi meteorological station is located about 70 km northwest from the Kõiguste study site, the Tallinn-Harku station about 17 km southwest from the Pirita study site. The climate data for the Vilsandi station were available from 1921. The precipitation data for the Tallinn-Harku station were available only from 1945.

Results

Radial growth of the stands

The values of the EPS show that the number of the sampled trees exceeds the minimum number of trees required to reach EPS equal to 0.85, a reasonable threshold for EPS (Briffa and Jones 1990). Higher EPS values indicate that a particular sample chronology portrays well the hypothetically perfect chronology.

Although the variation in the tree-ring widths of trees of the Pirita old stand, and especially during the young age seems high (Fig. 1) compared to that of the Kõiguste old stand (the mean sensitivity during this period 0.256 and 0.202, respectively), statistical analysis revealed larger variance in the measured ring-width series in both Kõiguste stands than in the series of the Pirita stands (Table 1). The similarity of the radial growth between old and between young generations of the stands was not high (synchronity 63.4% and 53.5%, respectively). The mean sensitivity was considerably high for the tree-ring series of the old generations of the stands but only slight differences between both old stands and between both young stands were apparent.

The similarity between the radial growth of the old and young stands during a common life interval of stands differed between study sites. On the Kõiguste study site the synchronity in radial growth between the old and young stands in 1957–2001 was moderate (65.9%) but the correlation between the tree-ring

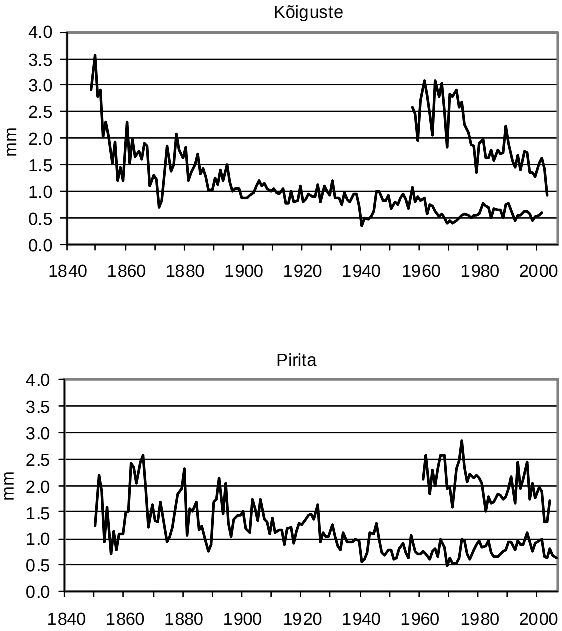

Figure 1. Tree-ring width chronologies of the Scots pine stands at the Kõiguste and Pirita sites. The graph of the chronologies of the young stands is shown above

Table 1. Statistical characteristics of tree-ring and latewood series

	Stands			
	Kõiguste old	Kõiguste young	Pirita old	Pirita young
Measurements				
Span of the series	1848–2001	1957–2001	1849–2004	1961–2004
Lenght, years	154	45	156	44
Sample depth, trees	13	17	14	16
Age of sampled trees, years	159–164	52–57	162–168	48–54
Tree-ring series				
Average tree-ring width, mm	1.04	2.07	1.12	1.93
Variance	0.29	0.32	0.19	0.20
Mean sensitivity	0.252	0.148	0.255	0.153
1st order autocorrelation	0.837	0.722	0.733	0.617
Latewood series				
Average latewood width, mm	0.39	0.67	0.35	0.63
Variance	0.026	0.028	0.019	0.046
Average latewood percentage	39.0	34.5	31.4	31.3
Mean sensitivity	0.388	0.353	0.400	0.361
1st order autocorrelation	0.634	0.194	0.537	0.614
Standardized chronology				
Tree-ring series				
Variance	0.04	0.02	0.05	0.02
Mean correlation between trees	0.242	0.386	0.365	0.384
Expressed population signal	0.856	0.910	0.889	0.897
Mean sensitivity	0.169	0.157	0.199	0.149
Signal-to-noise ratio	4.146	10.059	8.039	8.727
1st order autocorrelation	0.407	0.117	0.318	0.080
Latewood series				
Variance	0.07	0.07	0.09	0.04
Mean correlation between trees	0.325	0.448	0.383	0.388
Expressed population signal	0.863	0.928	0.897	0.898
Mean sensitivity	0.274	0.292	0.340	0.254
Signal-to-noise ratio	6.273	12.985	8.683	8.876
1st order autocorrelation	0.191	0.114	0.083	–0.194

widths was not significant (r = 0.16). At the Pirita study site the synchronity of the tree-rings widths between the old and young stands in 1961–2004 was also moderate (65.1%) but the tree ring widths were significantly (r = 0.40) correlated.

The average tree-ring widths of the old generations of stands were quite equal (Table 1). As regards the young stands, the Kõiguste young stand showed a slightly better radial growth compared to the young stand at the Pirita site although the difference was not statistically significant.

An increase in the radial growth from 1980 until 2000 can be observed in the plot of ring widths of both old stands (Fig. 1). The average tree-ring widths of the Pirita old stand during the periods from 1961 to 1980 and from 1981 to 2000 were 0.74 mm and 0.85 mm, respectively. For the Kõiguste old stand the average tree-ring widths during the same periods were 0.56 and 0.60 mm. Average tree-ring indices during these periods were 0.968 and 1.043, respectively for the Pirita old stand and 0.862 and 1.022, respectively for the Kõiguste old stand. A short-term increase in the radial growth of pines of the Pirita young stand in the early 1990s was detected. Nevertheless, the average tree-ring width in 1981–2000 (1.91 mm) was smaller than that in 1961–1980 (2.23 mm). The average tree-ring width of pines of the Kõiguste young stand during these two consecutive periods decreased as well (2.44 mm and 1.65 mm, respectively).

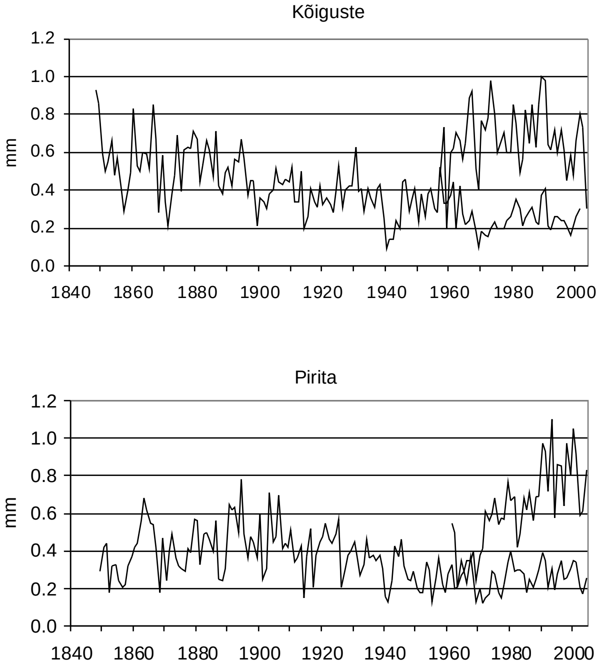

Figure 2. Latewood width chronologies of the Scots pine stands at the Kõiguste and Pirita sites. The graph of the chronologies of the young stands is shown above

Differences in the latewood width were negligible between the stands of the same generation but were significant between old and young generations at both sites (Fig. 2, Table 1). The average percentage of latewood was slightly larger in tree-rings of the Kõiguste stands whereas the differences were significant between the old generations of the stands. The mean sensitivity for the latewood series was considerably larger than for the tree-ring width series. No significant differences in the mean sensitivity between the stands of the same generation were detected.

No noteworthy changes in the average latewood widths between consecutive periods 1961–1980 and 1981–2000, as it was detected for tree-ring widths, were observed for either the Kõiguste stands or for for Pirita old stand. It was only in the case of the Pirita young stand that the latewood width increased significantly in 1981–2000 (average values 0.48 mm and 0.75 mm, respectively).

Radial growth of young and old stands at the same cambial age

Analysis showed that the radial growth of young generations at the age of 11–30, 11–40 and 11–50 years exceeded that of old stands at the same ages significantly (Table 2). The trends in the radial growth were descending in all stands (Figs. 3 and 4). Also the average latewood width of the young generations was significantly larger than for old generations at the same age but ascending trends were observed (Figs. 3 and 4). The radial growth of the young stands exceeds that of the old stands significantly even during the last decade when the differences in the average values of both tree-ring widths and latewood widths between the old and young stands were the smallest. Differences

Table 2. Average tree-ring and latewood widths (±SE) and average latewood percentage (±SE) of stands at different cambial age

Stand	Age, years	Average		
		tree-ring width, mm	latewood width, mm	latewood percentage, %
Kõiguste old	11–30	1.72±0.09	0.52±0.02	32.5±1.3
	11–40	1.63±0.06	0.53±0.01	34.2±1.0
	11–50	1.58±0.05	0.54±0.01	35.7±0.9
Kõiguste young	11–30	2.45±0.08	0.69±0.02	29.1±1.1
	11–40	2.23±0.08	0.71±0.01	33.0±1.3
	11–50	2.06±0.07	0.70±0.01	35.2±1.2
Pirita old	11–30	1.57±0.06	0.41±0.01	27.2±0.7
	11–40	1.51±0.04	0.43±0.01	29.3±0.7
	11–50	1.50±0.03	0.44±0.01	30.1±0.6
Pirita young	11–30	2.10±0.08	0.56±0.03	28.1±1.7
	11–40	2.04±0.06	0.62±0.02	31.7±1.5
	11–50	1.96±0.05	0.65±0.02	33.8±1.3

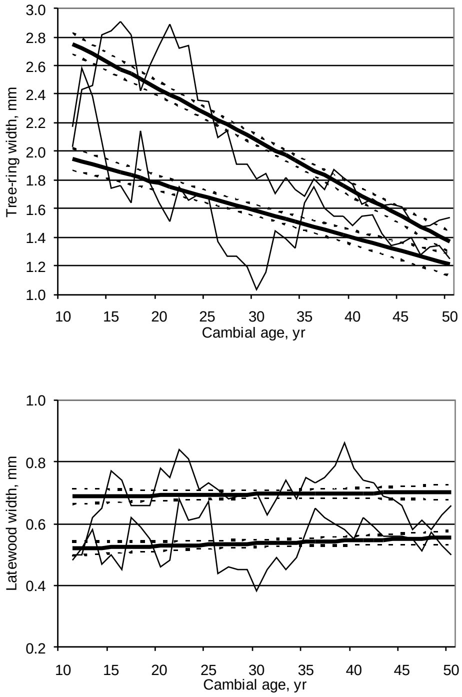

Figure 3. The tree-ring width and latewood width (mm) (solid lines), their linear regressions (bold solid lines) and significances levels of regressions (dash lines) of the Kõiguste stands at cambial ages from 11 to 50 years. The graph of the chronologies of the young stands is shown above

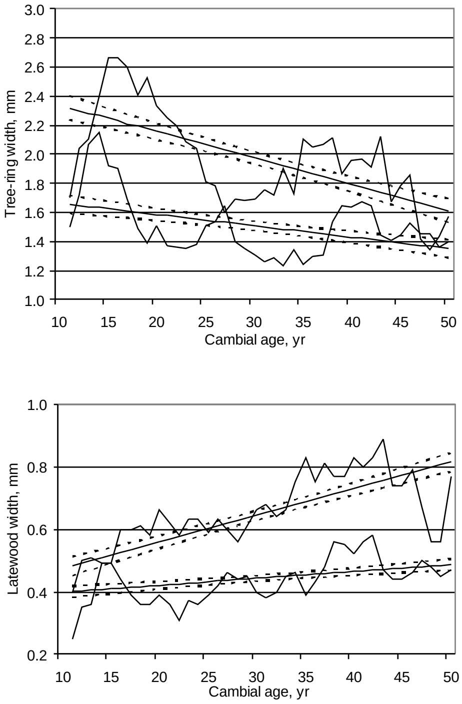

Figure 4. The tree-ring width and latewood width (mm) (solid lines), their linear regressions (bold solid lines) and significances levels of regressions (dash lines) of the Pirita stands at cambial ages from 11 to 50 years. The graph of the chronologies of the young stands is shown above

in the percentage of latewood were insignificant between the young and old generations of the stands.

Radial growth-climate relationships

Correlation analysis revealed that the radial growth of the old generations of stands was positively and significantly correlated with the average temperatures of the winter and early spring months (Figs. 5A and 5B). The radial growth of the old stands during the life period of the young stands was positively correlated with the temperatures of the winter months as well, but significantly with the March and April temperatures in the case of the Pirita old stand. The effect of the winter temperatures on the radial growth of the young stands and on that of the Pirita old stand during its young age was positive as well but mostly statistically not significant. A significant correlation was found only between the radial growth of the young Kõiguste stand and the average February temperature. The May temperature had a significant negative effect on the radial growth of the young Pirita stand. A notable positive correlation with the temperatures of the early summer months (June and July) of the previous growing season was found in the case of both young stands.

The temperatures of the summer months in the previous as well as the current growth season did not have an essential effect on the radial growth of the stands.

Age-dependent tree-ring growth response of old stands to the main climatic factor forcing the radial growth, winter temperature, was detected. The correlations between the radial growth of the Pirita stand and the mean winter temperatures (January–March) were low ($r < 0.20$) and statistically not significant up to about 70 years of age, reached the maximum values ($r = 0.31$) at the age of 130 years and decreased slightly at the age of 150 years ($r = 0.28$). The age effect was more clearly expressed in the case of the Kõiguste old stand. Because of the lack of the climate data up to 1920 correlations between the radial growth and winter temperatures were not calculated for the earlier period of the life of this stand. At the age of approximately 90 years the correlation coefficient was high ($r = 0.72$) but was followed by a decrease (to $r = 0.35$) at the age of 150 years. In both cases the trees retained their significant sensitivity to winter temperatures at the end of the analysed period, however.

Approximately similar results were obtained when the latewood widths of the old generations instead of the tree-ring widths were used in analysis (Figs. 6A and 6B). In addition, a strong positive effect of the average temperatures of the spring months on the latewood width can be observed. In the case of the young generations the winter temperatures were mostly positively but not significantly correlated with the latewood widths. Only the average temperatures of March revealed a significant effect on the latewood widths of the Pirita young stand. The late winter and early spring temperatures had a strong positive effect on the latewood width of the Pirita old stand during its young age as well. Correlation coefficients between the latewood width and late summer and autumn temperatures of both, the previous and the current growth

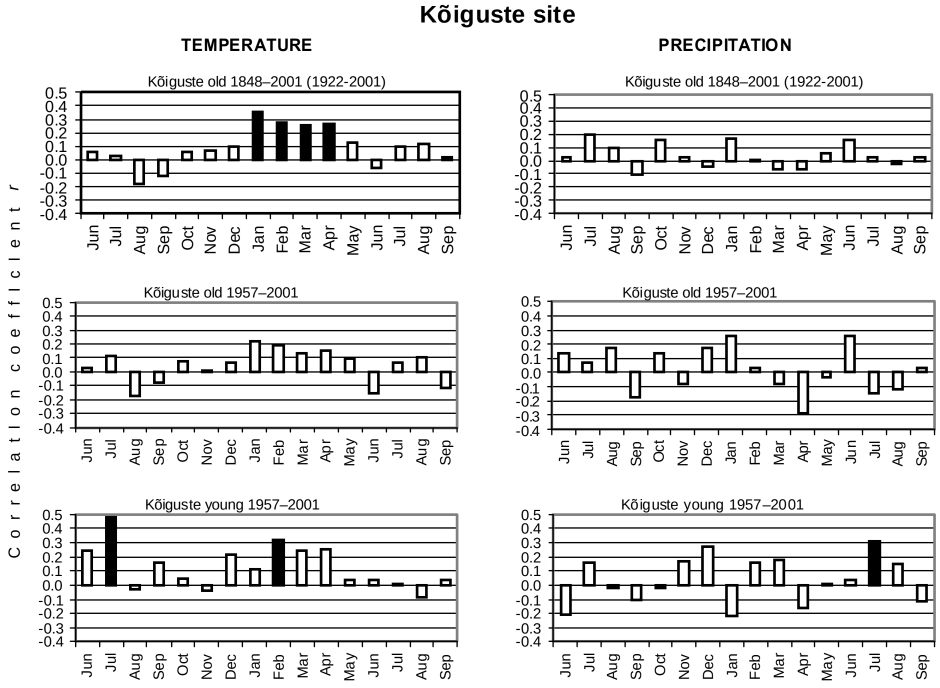

Figure 5A. Correlation coefficients between the tree-ring widths and climate variables at the Kõiguste site. Black bars stand for statistically significant correlations ($p < 0.05$)

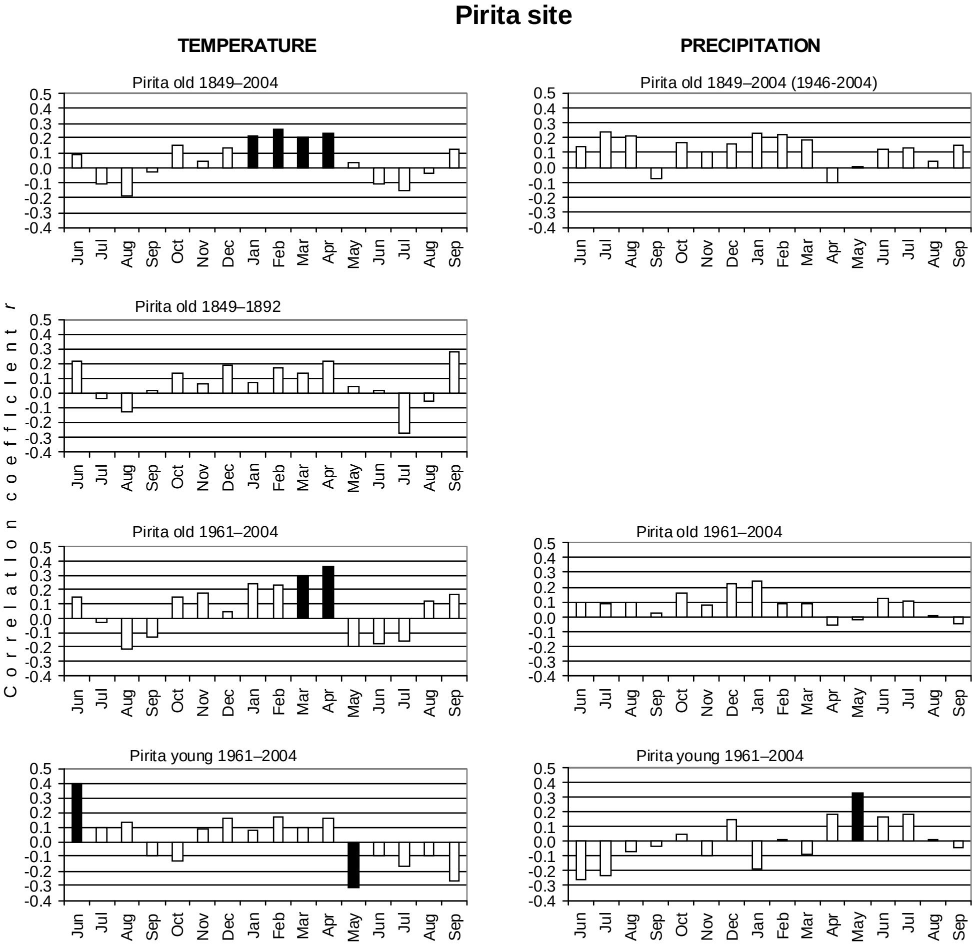

Figure 5B. Correlation coefficients between the tree-ring widths and climate variables at the Pirita site. Black bars stand for statistically significant correlations ($p < 0.05$)

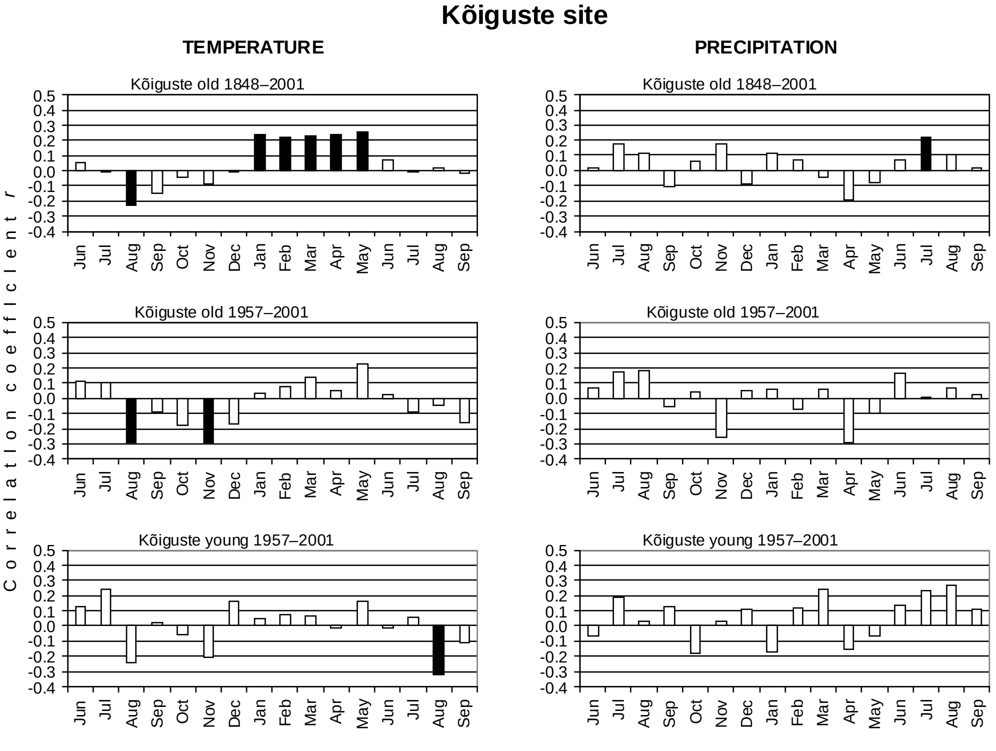

Figure 6A. Correlation coefficients between the latewood widths and climate variables at the Kõiguste site. Black bars stand for statistically significant correlations ($p < 0.05$)

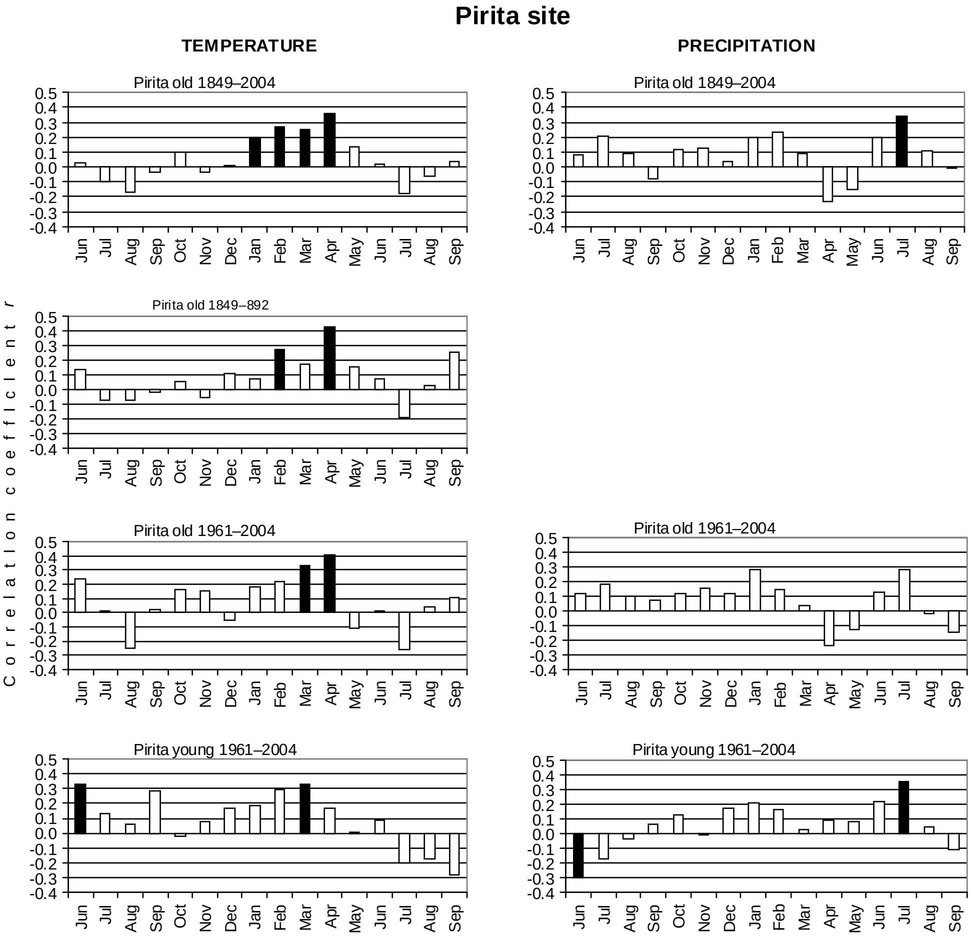

Figure 6B. Correlation coefficients between the latewood widths and climate variables at the Pirita site. Black bars stand for statistically significant correlations ($p < 0.05$)

season were mostly negative and close to zero. Only in the case of the Kõiguste old stand temperatures in the previous season's August and November had a significant but negative effect on the latewood formation in the next season. The warm August in the current growth season decreased substantially the latewood width of the trees of the young stand at the same site.

No significant relationships between total precipitation and the radial growth of the old stands of any month were detected. The significant positive effect of the May precipitation on the radial growth of the Pirita young stand and of the July precipitation on that of the Kõiguste young stand was revealed. Generally the monthly total precipitation had no significant effect on the latewood width except for the strong positive impact of precipitation in the July of the current growing season in all stands.

Discussion

The radial growth of two consecutive generations of Scots pine stands at the same site unit in the same site conditions was investigated in this study in order to deduce whether the present young stands showed higher growth rates than old generations of stands at the same age.

Radial growth of the stands

The marked differences between the variances in the measured tree-ring width series of the Kõiguste and Pirita stands are obviously a result of a sharp decrease in the radial growth in the 1850s of the Kõiguste old stand and in the 1970s of the Kõiguste young stand. The radial growth of pines of the Pirita old stand did not follow the classical shape of the growth curve of Scots pines, which is commonly best described by a negative exponential. The reason of the sharp fluctuation of the tree-ring widths with intervals of 13–15 years of the old stand at this site during its young age is still unknown. Relationships between winter temperatures, the mean climate variables forcing the radial growth of pines in our region, and the radial growth, were weak in this case. The possible effect of solar activity on the radial growth during that period was not studied in this work, however.

The low correlation between the radial growth of the young and old stands at the Kõiguste site during the common life period may be influenced by changes in the response of growth to the climate variation with the ageing of trees. The age-dependent tree-ring growth response to climate was detected for various tree species including white spruce (*Picea glauca* (Moench) Voss) by Szeicz and MacDonald (1994) in western Canada, *Larix decidua* and *Pinus cembra* in Italy (Carrer and Urbinati 2004), and Scots pine in the Scandinavian Mountains (Linderholm and Linderholm 2004) and in the Scottish Highlands (Fish et al. 2010) and in the case of both old generations of stands in this study. The discrepancies between the responses of stands of different age to climate may reflect changes in functional processes strongly coupled to tree growth with increasing tree age. No significant differences in the growth–climate relationships between the old and young trees during their common growth period at the Pirita site were detected, however.

Radial growth of young and old stands at the same cambial age

Analysis showed greater tree-ring width of young generations at cambial ages of 11–30, 11–40 and 11–50 years compared to old stands at the same cambial age. The higher growth rates of young generations were more pronounced for earlier cambial ages but remained statistically significant even during the last decade. The larger ring widths of the Kõiguste stands at each age compared with those of the Tallinn stands were obviously caused by the more favourable site conditions.

At the present time, the main factors, that may cause changes in the growth rates of stands, are the improved management practices (intensive tending of stands, preference of plantation to seed etc.), deposition of nitrogen, possible increase in CO_2 in the atmosphere and possible long-term changes of temperature among others (Wenk et al. 1990, Spiecker et al. 1994, Erlickyté and Vitas 2008, Bolte et al. 2009,. McMahon et al. 2010). In this study the single-species pine stands were of natural origin without any known management history. Therefore the greater radial growth of the young generations was obviously not due to silvicultural measures.

The supply of inorganic nitrogen in soils is considered as the most important factor limiting the growth of boreal forests (Aber et al. 1989, Vestgarden et al. 2003). The global atmospheric nitrous oxide concentration increased from a pre-industrial value of about 270 ppb to 319 ppb in 2005 and that of carbon dioxide of about 280 ppm to 379 ppm (IPCC 2007). As a consequence of the increased emissions of N compounds elevated deposition rates of N on the earth's surface are observed (Holland et al. 2005). Increased deposition of N from the atmosphere is considered as at least a partial reason of both the worsening of the forest health in the regions with heavy loads of industrial wastes (Nihlgård 1985, Skeffington and Wilson 1988, Ozolincius et al. 2005) and of the positive trend in the forest growth in various parts of Europe (Kenk and Fischer 1988, Schneider and Hartmann 1996). The findings from earlier studies indicate the significant effect of N fertilizers on the increment of pine stands on N-poor sandy soils (Valk et al. 1985). The long-term average N deposition in Estonia is rather moderate (3–6 kg ha^{-1} yr^{-1}, Riikliku keskkonnaseire... 2005) but may have a certain effect on the tree growth on nutrient-poor soils.

On the other hand, experiments have shown a positive effect of increased CO_2 concentration in the atmosphere on the growth of trees (Loats and Rebbeck 1999, Hamilton et al. 2002). Due to the intense combustion of fossil fuels and of the decrease of the forested lands the emissions of CO_2 into the atmosphere have considerably increased during the last 200 years. As result the global CO_2 atmospheric concentration increased by 35.4% from a pre-industrial value (WMO Greenhouse… 2006).

We have no evidence about the application of fertilizers in the studied stands. The Saaremaa site stand is previous collective farm forest and the Tallinn site stand belonged to the so-called "green belt" forests around Tallinn city. Fertilization of such forests was considered as unnecessary during the period of intense fertilization of Estonian forests in the second half of the last century. Thus for the growth of the studied young stands, the increased N deposition and elevated CO_2 level during the second half of the 20th century may have had some positive influence, particularly in the case of the Tallinn stands, growing on nutrient-poor sandy soil.

Radial growth–climate relationships

The negative effect of the low temperatures during the winter months on the growth of pines in the following season in the Baltic region has been shown by several authors (Битвинскас 1974, Шпальте 1978, Lõhmus 1992, Vitas and Bitvinskas 1998, Pärn 2002; Läänelaid and Eckstein 2003, Hordo et al. 2009). Positive relationships between mean temperatures of the winter and early spring months and the radial growth of the studied stands and were detected by the given study as well. The higher temperatures during this period seem to have had a significant positive effect on the radial growth of both older generations of stands. In the case of the young generations of stands the effects of winter temperatures on the radial growth differed between the stands. The results indicate significant positive relationships in the case of the young generation of the Kõiguste stand. The effect of the winter temperatures on the radial growth of the young Pirita stand is positive but statistically nonsignificant regardless of the about 2 degrees lower long-term average temperature of the winter months compared to winter temperatures at Kõiguste. It is noteworthy that the radial growth of the old generation of the Pirita stand was not much influenced by temperatures of the winter months during its young age.

The dependence of the growth of pines during the current season, especially in the northern regions, on the conditions of the previous season has been demonstrated in several studies (Hustich 1978, Lindholm 1996). The effect of a favourable or unfavourable growth season is carried over in various ways into the following years. The formation of earlywood, i.e. the inner part of the treen ring formed in the spring, depends at least partly on the quantity of nutrients stored in the tree over the winter (Leikola 1969). Positive correlations between the radial growth and mean monthly temperatures of the previous June and July were reported earlier in Pärn (2003) and the results for the young pine stands in this study support these findings.

Approximately similar results were obtained when latewood width were used instead of the tree-ring widths in analysis. Generally, a fairly strong positive effect of the mean temperatures of the spring months on the latewood width can be observed. The positive impact of a warm spring on the latewood width detected in this study is in accordance with the results of other studies. A strong link between the latewood width and spring temperatures was described by Miina (2000) for Scots pines in eastern Finland, by Savva et al. (2003) for pines from different provenances in Russia and by Drobyshev et al. (2004) for pines in the Komi Republic. A warm spring creates preconditions for an earlier beginning and thus a longer duration of the growing season.

Of parameters that characterize the moisture regime the precipitation in summer months has been reported to have some positive importance in the growth of an annual ring in the Baltic region (Lõhmus 1992, Vitas and Bitvinskas 1998). The results of the present study indicated that the impact of precipitation was generally less important than temperature on the radial growth. Only the precipitation sum in July had a considerable impact on the radial growth and latewood formation of both young stands and the Tallinn old stand.

According to the observations made in the Tallinn-Harku meteorological station, the average temperature of the winter months in 1950–2000 was by 1°C higher compared to that in 1850–1900. The regression values of the precipitation sums in July increased from 64.2 mm in 1945 to 85.2 mm in 2006. Therefore, the fact that the radial growth of the studied pine stands and temperatures of winter and early spring months and precipitation in July are directly correlated may give a reason to assume that long-term continuous warming and increasing moisture are causes, at least partly, of the increasing growth of young generations of pines.

Conclusions

The changes in the radial growth in two consecutive generations of pine stands at two sites were investigated. Analysis showed that the radial growth of young generations at the ages of 11–30, 11–40 and 11–50 years exceeded that of old stands at the same age. These differences decreased with the increasing age of the stands. For the growth of the studied young stands, the increased N deposition and elevated CO_2 level during the second half of the 20th century may have had some positive influence. Considering the rising average temperature of the winter months and increasing total precipitation in July during the last century it may be assumed that long-term climate change may have caused, at least partly, the increasing growth of young generations of pine. The relationships between the climate and radial growth of trees revealed in this study may depend on characteristics of the forest site type and geographical locality where the trees are growing and thus may be limited geographically. Therefore, more research is needed before extrapolating the results to other forest types and regions.

Acknowledgements

The research was supported by the Estonian Ministry of Education and Research (project No. 0170021s08).

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Received 26 April 2011
Accepted 18 May 2012

ИЗМЕНЕНИЯ РАДИАЛЬНОГО ПРИРОСТА ДВУХ ПОСЛЕДОВАТЕЛЬНЫХ ПОКОЛЕНИЙ СОСНЫ ОБЫКНОВЕННОЙ (*PINUS SYLVESTRIS* L.)

Х. Пярн

Резюме

Были исследованы изменения в радиальном приросте двух последовательных поколений сосны обыкновенной. Древостои росли рядом в сходных условиях произрастания. Их возраст – 160 и 55 лет. Различия в радиальном приросте двух поколений древостоев были оценены сравнением средней ширины годичных колец в камбиальном возрасте 11-30, 11-40 и 11-50 лет. Анализ показал, что радиальный прирост молодых поколений превысил радиальный прирост старых древостоев в том-же камбиальном возрасте. Различия в средней ширине годичных колец уменьшались с возрастом древостоев. Нарастающая депозиция азота и повышенный уровень двуокиси углерода в атмосфере в течение второй половины 20 века могут оказать позитивное влияние на радиальный прирост молодых древостоев. Одновременно, повышение зимних температур и увеличение осадков в июле, имеющие существенное влияние на радиальный прирост сосновых древостоев в регионе данного исследования в течение прошлого столетия, связанные с потеплением климата, несомненно содействуют улучшению роста сосновых древостоев.

Ключевые слова: сосна обыкновенная, годичное кольцо, поздняя древесина, изменние климата