Development of a Tree-ring Chronology of Scots Pine (*Pinus sylvestris* L.) for Estonia as a Dating Tool and Climatic Proxy

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In order to build a tree-ring chronology for Estonia, as a dating tool and climatic proxy, we investigated whether the whole country can be considered to be dendrochronologically uniform. Seven sites with living pine trees throughout the country were chosen, and the tree-ring series cross-dated between each site. A principal component analysis of the variance of the tree-ring widths as well as a cross-correlation between all individual tree-ring series revealed that Estonia is a homogenous dendroclimatic area for pine. Accordingly, the climate-growth relationship was calculated on the basis of one overall tree-ring chronology. As a result, winter/early spring temperature was revealed to have a strong positive influence on the radial growth of pine. This climatic signal was extracted from a part of the existing Estonian composite pine tree-ring chronology and, in extreme cases, validated from archival records.

Key words: Estonia, pine growth, tree-ring chronology, winter/early spring temperature

Introduction

Scots pine (*Pinus sylvestris* L.) is one of the most common tree species in Estonia along with Norway spruce (*Picea abies* (L.) Karst.) and birches (*Betula pendula* Roth. and *B. pubescens* Ehrh.). Together with Norway spruce, it is also the most common construction timber used in Estonia today and in the past. The assemblage of a tree-ring chronology of Scots pine is therefore of great importance for the dating of historical buildings, and thus for the conservation of monuments in Estonia. First of all, the question of whether all living trees and building timbers can be considered to originate from one dendroclimatic region has to be answered. If that is the case, one chronology of pine for the whole of Estonia can be built; otherwise, several regional chronologies must be established. A tree-ring chronology, once assembled, contains climatic information that may be useful for the study of the climate history of the country, if not of the whole Baltic region. The present study is therefore aimed at constructing a pine tree-ring chronology as a dating tool, and at extracting the climatic signal from it.

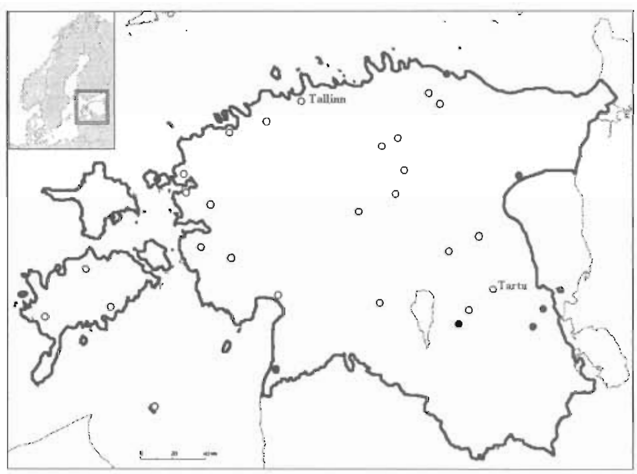

Figure 1. Map of the Baltic Sea area showing the location of Estonia and the sites of the forests (black dots) and of some architectural monuments (rings)

Study area (Fig. 1)

The territory of Estonia covers 45 100 km^2, extending ca. 270 km from north to south and ca. 390 km from east to west (including the sea islands). It is a low and flat country with an average elevation of 50 m a. s. l.; the highest elevation is 318 m a. s. l. The local climate can be characterized by warm summers and temperate mild winters influenced by the Atlantic Ocean and modified by the Baltic Sea. The average annual air temperature in Tartu is +4.7° C; the average sum of annual precipitation is 550-650 mm. The vegetation period (with an average air temperature above 5°) is 170-185 days long. Forests cover about half of the territory of Estonia. The largest forests can be found in the northeastern and southwestern parts, but smaller forests are present everywhere. Therefore we can assume that the building timbers of the architectural monuments are of local origin and consequently contain the same climatic signal as the living trees.

Material and methods

Seven forest sites were chosen for sampling old-aged living pine trees (see Fig. 1). Pines of hundreds of years of age also grow in raised bogs, but they were not included since they were never used in building. The forest sites chosen were Järvselja and Kiidjärve in the SE, Raadna in the NE, Karepa in the N, Vormsi in the NW and Häädemeeste in the SW of Estonia (Fig. 1). Järvselja and Kiidjärve represent *Rhodococcum vitis-idaea* sites; Raadna, Karepa, Häädemeeste and Vormsi are *Rhodococcum vitis-idaea* sites on sandy soils. The samples referred to as Verevi have been extracted from recently cut building timber; their site conditions are not well known. On each site, 12 pine trees were cored at breast height using an increment borer, one core per tree; only at Raadna, the pines were cored from two opposite sides of the trunk.

All 84 raw tree-ring series were cross-dated and then processed by the software ARSTAN (Grissino-Mayer, Fritts 1997) in order to remove the age trend and other non-climatic variability and then to produce a so-called residual chronology for each site, which is characterized by an autocorrelation of zero. The standardization was performed in two steps, in the first step a negative exponential regression function and in the second step a 64-year spline function was fit to the data. The chronologies were then computed using the bi-weight robust mean function. These seven site chronologies were used in a principal component analysis, as well as a cross-correlation analysis, to evaluate both the common variance and the similarity between the sites (Wazny, Eckstein 1991).

Then, a mean chronology produced from all seven site-chronologies was processed using the PRECON program (Grissino-Mayer, Fritts 1997) for receiving climate-growth relationships on the basis of simple correlations between tree-ring width and the contemporaneous climate. For the climate data, monthly mean temperatures and precipitation sums from previous September to current August were taken over a period of 120 years (1879-1998). The Tallinn meteorological station recorded the monthly air temperature. The precipitation data was averaged from a number of records of meteorological stations over the territory of Estonia (the averaged data was made available by the Institute of Geography of the University of Tartu). A complete table of monthly air temperatures in Tallinn during the period 1756 - 2002 has been published recently by Tarand (2003). We also used historical records of extraordinary weather events in Estonia from 1713 to 1870, compiled from several sources by Vahtre (1970).

Apart from the 84 living trees, series of 204 pine building timbers from architectural monuments, which had been sampled during the last years, were included (Läänelaid 1999). The locations of some of the monuments are also shown in Figure 1; two examples of these objects are given in Figure 2a and 2b. All the raw data from the living trees and from the building timbers was merged into one regional tree-ring chronology by the dendrochronological overlapping technique; some dendrochronological dating examples have been given by Läänelaid (1996, 1997, 2002). This so-called Estonian regional pine chronology was standardized and used as a climate proxy in a straightforward manner.

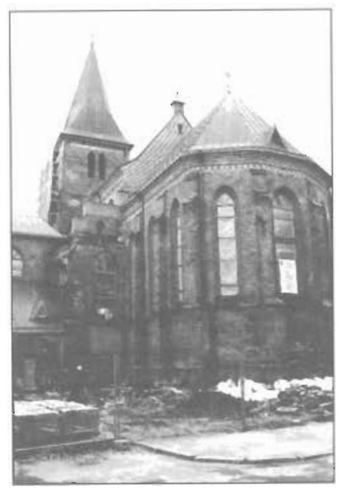

Figure 2a. St. John's Church in Tartu, Estonia. The red brick walls stand on several layers of pine beams in a swampy soil; dendrochronology revealed the last growing year of the pines as AD 1320

Figure 2b. Former Cistercian convent (now Gustav Adolph Gymnasium) in Tallinn, Estonia; ceiling beams of a cellar carrying limestone plates; the beams are partly covered by white fruit bodies of a fungus. Dendrochronology proved the last tree ring of the beams to be from AD 1448

Results

Checking the uniformity of the study area

The distribution of the seven site chronologies along the axes of the first two principal components of the tree-ring width variability (Fig. 3) shows that the 1st principal component values are quite similar to each other, whereas along the 2nd principal component a wide differentiation is revealed. The dense cluster of the site chronologies along the 1st principal component, which represents 57% of the total variability, refers to a uniform factor that has affected tree growth variability; apparently this factor is climate. This assumption is supported by comparing the similarities versus the distances between all seven site chronologies (Fig. 4); there is no correlation between these two variables. The 2nd principal component represents 10% of the total tree-ring width variability and represents the differences between the sites.

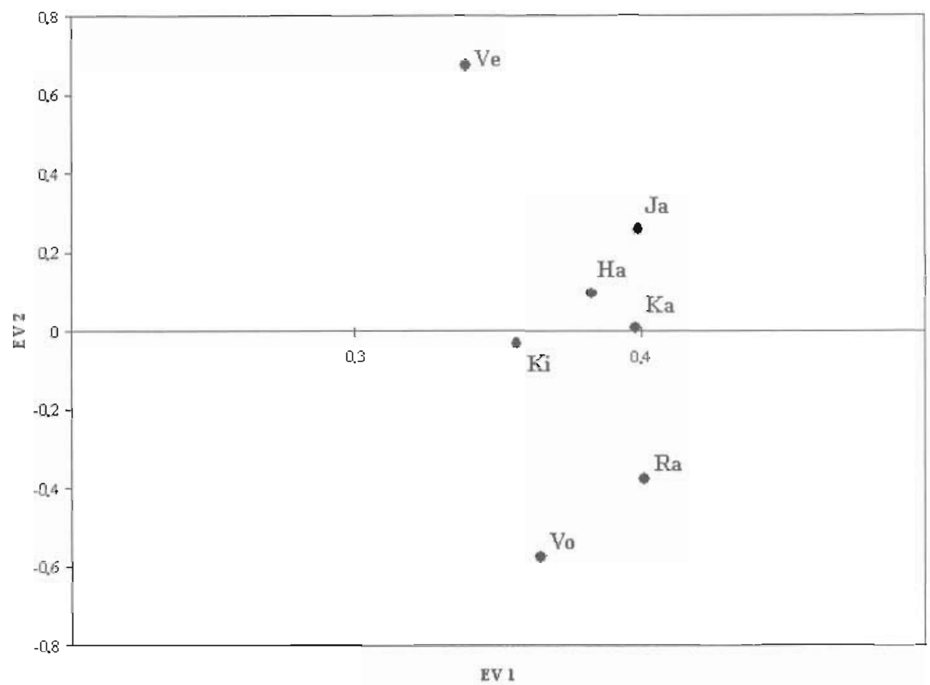

Figure 3. Distribution of the site chronologies along the axes of the first two principal components on the basis of the weights of the first and second eigenvector. Abbreviations of sites: Ha = Häädemeeste, Ja = Järvselja, Ka = Karepa, Ki = Kiidjärve, Ra = Raadna, Ve = Verevi, Vo = Vormsi

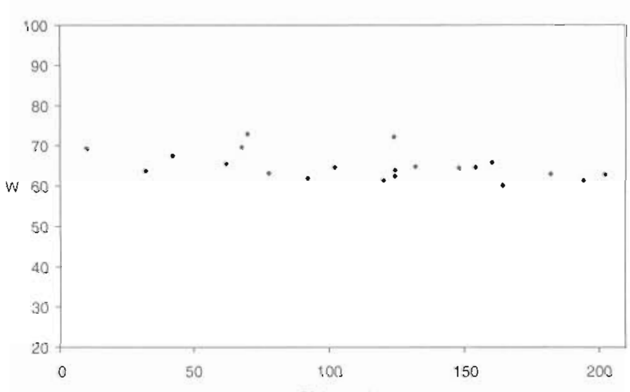

Figure 4. Similarity, measured by the sign test W (Eckstein, Bauch 1969), vs. distance in kilometers of seven Estonian site chronologies

Climate-radial growth relationship

The climate-growth relationship of the Estonian pines is graphically described in Figure 5. The whole period, from 1879 to 1998, for which climatic records with monthly values of temperature and precipitation were available was subdivided into five 40-year-long sub-periods overlapping each other by 20 years. Evidently, winter/early spring temperature from December to April, sometimes even May, has the strongest influence on pine growth, i.e. above-average warm winters favor growth during the subsequent summer season, and vice versa. On the other hand, precipitation seems not to be a growth-limiting factor at all; there is only a weak tendency for above-average rainfall during the growing season to have a positive influence on the growth of pine. In consequence, winter/early spring temperature is defined as the climatic signal contained in the Estonian pine tree-ring series.

Assembling an Estonian pine chronology as a dating tool

Along with the tree-ring series of living pines, the tree-ring series of dated architectural timber were averaged into one Estonian pine tree-ring series, including altogether 281 single tree-ring series. The extent of this chronology is the 483 years between 1998 and 1516.

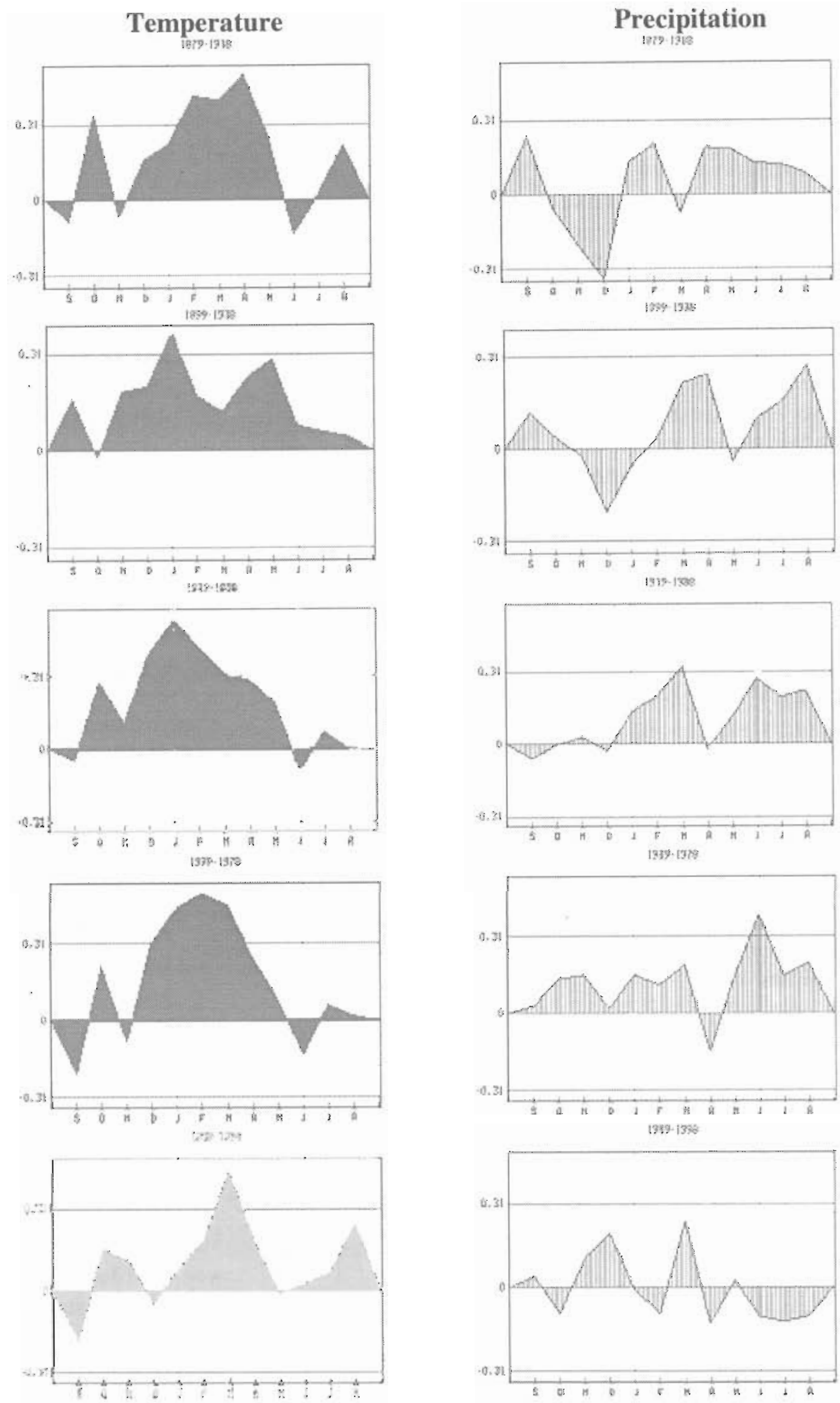

Figure 5. Correlation of the Estonian pine chronology with monthly temperature and precipitation between the previous September and the current August in five 40-year "windows"; the horizontal line through 0.31 marks the significance level of 0.95. Abscissa - months from September to August, ordinate - coefficients of correlation

Besides, there are two older mean tree-ring series of architectural timber, one from Gustav Adolph Gymnasium in Tallinn, covering 152 years (Fig. 2b) and one from St. John's Church in Tartu, covering 196 years (Fig. 2a). Both mean tree-ring series do not yet overlap with the Estonian pine tree-ring chronology, but overlap with each other by 24 years, and thus result in a 324-year-long chronology. They were dated independently with Scandinavian and Russian pine chronologies (Läänelaid 2002) and cover the time between 1448 and 1125.

The Estonian pine chronology as a climate proxy

The composite pine chronology is used straightforwardly as a proxy for winter/early spring temperature, as illustrated in Figure 6, where the pine chronology and the average December to April temperature run very nearly parallel from the present day back to 1880. The average monthly temperature in Tartu from 1879 to 1998 is in December -4.1° C, in January -6.4° C, in February -6.5° C, in March -2.9° C and in April 4.0° C. From this extraordinarily good similarity it appeared reasonable to go beyond the limits of this record (Fig. 7). It could be confirmed that the extremely narrow tree rings before 1880, with few exceptions, are also an indication of severe winters in the eastern Baltic region at that time. The climatic information necessary for verification was taken from Vahtre (1970):

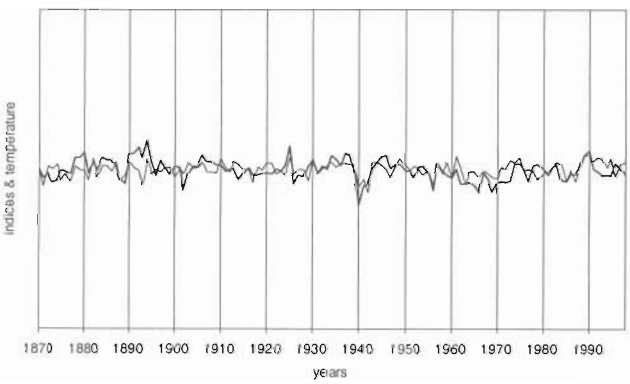

Figure 6. Average tree-ring indices of 182 Estonian pines (bold line) and winter (XII-IV months) temperature between 2000 and 1870

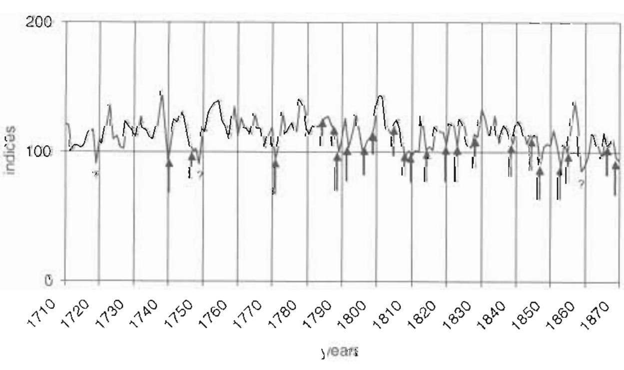

Figure 7. A part of the average curve of tree-ring indices of 182 Estonian pines between 1870 and 1710, with arrows pointing to cold winters notified in chronicles (Vahtre 1970); ? means either narrow tree rings without evidence of a cold winter or relatively wide tree rings after a recorded severe winter

1869 – year began with cold of up to -23.2° in Tartu. Monthly average temperature: -8.63° in Tartu and -5.8° in Tallinn. February warm. First half of April warm, temperature nearly +20°. Then cold again and snow.

1868 – December 1867 very cold, monthly average: -9.73° in Tartu, -7.9° in Tallinn. Beginning of January 1868 melting, but then strong cold: up to -30° in Martna in west Estonia and -36.2° in Tartu. Lots of snow. Monthly average temperature in January: -11.12° in Tartu and -8.1° in Tallinn. In February melting. From the end of May extraordinarily dry until September; crop failure throughout Europe.

1867 – year started extremely cold: on 19 January -31° and on 20 January -33°, with NE wind, near Viljandi/south Estonia. In Pärnu/west Estonia: -31 to -34°; average January temperature in Tartu/east Estonia was -11.26°, in Tallinn harbor -9.8°; lots of snow. From end of January to beginning of February a longer melting period, then cold again; in February: -33.1° in Tartu. March colder on average than February; at the end of March, heavy snowfall with wind; April was a winter month, with abundant snow; even May was extraordinarily cold, monthly average: +3.82° in Tartu and +1.9° in Tallinn. On 10 May, snow in Tallinn like in February. Last severe night frost on 1 June.

1855 – February very cold, the average monthly temperature in Tallinn: -12.5°; the cold lasted until mid-March; spring dry and cool.

1853 – winter 1852/53 began in October; coldest was first week of March: in Tallinn, -24.5°, in Palamuse/east Estonia, -27.5°; cold lasted until the end of March.

1847 – winter started mid-November 1846 and lasted to mid-April. February 1847 colder than usual. On 24 January and 5 February, -24° in Tallinn. May cold, with night frosts and northern wind.

1845 – severe and continuous cold at the beginning of the year. February also cold. On the night of 22 February: -26° in Tallinn. Spring cold and dry.

1839 – winter lasted long, coldest month was March (average temperature in Tallinn -8.6°), and April was cold too.

1829 – January cold (monthly average -13.0°), also February (-11.5°). Relatively cold were March (-8.25°) and April (-1.5°).

1823 – January very cold, average monthly temperature: -15.5°; on 5 and 26 January: -29°; abundant snow. February mild, about 0°. Weather in April was changeable but generally cool until the beginning of May.

1820 – November and December 1819 very cold, average monthly temperature: -7.8° and -13.5°, respectively. In 1820 the severe cold continued. On 25 January, -22.5° in Tallinn.

1814 – winter 1813/14 very cold (on 24 Dec. -36° in Ruhja/north Latvia), lots of snow; beginning of April, warm, then cold until end of May. Many old fruit trees frozen.

1810 – winter 1809/10: not very cold, but long lasting (in Tallinn March was colder than January); spring was extraordinarily cold; frost and snow even on 28 May.

1808 – winter generally mild but long, and quite cold in February.

1805 – October 1804: cold came early, November and December with lots of snow. A cold and snowy winter. Coldest day was 6 February, with -24°. Spring was late, cold lasted until mid-June.

1799 – cold without snow in October 1798, December moist and cold; colder in January 1799; -29° on 4 February in Tallinn, -37.5° on some days at Laiuse in east Estonia; in February, mostly between -20 and -25°; extraordinarily cold in March, -24° on 17 March.

1796 – beginning of December 1795, severely cold, then melting alternating with cold periods; in January 1796, snow melted and cattle were let out to pasture; then cold again on 26 January; March rather cold, April and May rainy.

1792 – winter 1791/92 remarkably colder than the two previous winters; in Tallinn, -25°, in Curland, even in March, -30°; rainfall during the whole of April.

1789 – December 1788: extraordinarily cold, temperature continuously at about -25°, on 12 and 16 December, even -30° at Palmse in north Estonia; in January: -25° at Palmse and -23° in Tallinn in north Estonia. May cool, with night frost on 30 May.

1787 – from January to March, rather cold in Palmse in north Estonia; in April snow melted, then it turned cold again; only 20 July was a warm day, but nights of 18 and 24 July, cold; continuously raining, crop failure.

1785 – January generally mild; February very cold with snowfall. Snow and cold continued into March; April generally cold. May very rainy and cool with severe night frosts until 13-16 May.

1748 – winter 1747/48 severe and long, from Christmas to end of March without melting.

1740 – winter 1739/40 extremely cold, considered the coldest winter – together with the winter 1607/08 – during the last millennium; the entire Baltic Sea was frozen.

Discussion and conclusions

Dendroclimatological investigation of pines has been carried out in Estonia since the late 1970s (Läänelaid 1981). Now it has become possible to use modern methods and obtain statistically reliable results by using representative data from all over Estonia.

The results provide justification for the standpoint that Estonia is a uniform dendrochronological region and that pine timber from Estonian buildings and excavations should be datable by a single reference chronology averaged over the whole of Estonia. The dating success will, however, be favored by tightening the network of sites of historic wood samples, especially in the northeast and south of Estonia. Tree-ring samples are also required to fill the 80-year gap from 1527 to 1449 and to extend the existing tree-ring chronology further back into the past for both purposes, viz. dating cultural objects and reconstructing past climate.

From the dendroclimatic analysis, high winter/early spring temperature was found to have a notable positive influence on tree growth. This result opens a new possibility for detecting extreme cold winters, even for the time where no meteorological records are available. This is more rewarding for the fact that most climate reconstructions based on tree rings are related to temperatures in the growing season (Pfister *et al.* 1996). The extremely narrow tree rings and the low winter/late spring temperature seem to be connected by a specific air pressure pattern, the so-called North Atlantic Oscillation (Lindholm *et al.* 2001).

The range of the climatic signal of the Estonian pines appears to extend far into the neighboring countries, e.g. to Lithuania (Pukiene 2002), Latvia (Zunde 2003), western Russia (Bartholin, pers. comm.), southern Finland (Lindholm *et al.* 1997), Gotland (Bartholin, pers. comm.) as well as northern Poland (Cedro 2003). Future joint studies of dendrochronologists within this climatic and geographical region should try to determine, systematically, the real extent of the winter/early spring temperature signal.

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ПОСТРОЕНИЕ ХРОНОЛОГИИ ГОДИЧНЫХ КОЛЕЦ СОСНЫ ОБЫКНОВЕННОЙ (*PINUS SYLVESTRIS* L.) ЭСТОНИИ КАК СРЕДСТВО ДЛЯ ДАТИРОВАНИЯ И ИЗУЧЕНИЯ КЛИМАТА ПРОШЛОГО

А. Лянелайд, Д. Экштайн

Резюме

В разных частях Эстонии для составления хронологии годичных колец сосны обыкновенной (*Pinus sylvestris* L.) были выбраны семь участков с преобладанием старых деревьев. Все полученные ряды годичных колец синхронизировались перекрестным методом друг с другом и между участками. Статистический анализ главных компонентов показал, что Эстония является дендроклиматически гомогенной для сосны. Исходя из этого, для дальнейшего дендроклиматологического анализа использовалась единая хронология сосны. При этом выяснилось, что сильное положительное влияние на ширину годичных колец оказывали среднемесячные температуры периода зимы-ранней весны. Этот вывод был проверен сравнением графиков ширины годичных колец и метеорологических данных последнего столетия и более ранних архивных материалов, что показало хорошую сходимость.

Ключевые слова: Эстония, прирост сосны, хронология годичных колец, температура зимы-ранней весны