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KRISTINA SOHAR

Oak dendrochronology and climatic signal in Finland and the Baltic States

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PRESS

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This thesis is based on the following papers that are referred to in the text by Roman numerals.

I Läänelaid A, **Sohar K**, Meikar T (2008) Present state and chronology of oaks in an oak forest in Saaremaa Island, Estonia. Baltic Forestry 14:34–43

II **Sohar K**, Vitas A, Läänelaid A (2012) Sapwood estimates of pedunculate oak (*Quercus robur* L.) in eastern Baltic. Dendrochronologia 30:49–56

III **Sohar K**, Helama S, Läänelaid A, Raisio J, Tuomenvirta H (2014) Oak decline in a southern Finnish forest as affected by a drought sequence. Geochronometria 41 (In press: DOI 10.2478/s13386-013-0137-2)

IV **Sohar K**, Läänelaid A, Eckstein D, Helama S, Jaagus J (201X) Dendroclimatic signals of pedunculate oak (*Quercus robur* L.) in Estonia. European Journal of Forest Research (Submitted)

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I The author participated in the data collection, the laboratory work, and the writing of the manuscript.

II The author participated in the study design and the data collection, was fully responsible for the laboratory work and the data analysis, and led the writing of the manuscript.

III The author participated in the study design and the data collection, was fully responsible for the laboratory work, shared responsibility for the data analysis, and led the writing of the manuscript.

IV The author participated in the study design, did most of the data collection, was fully responsible for the laboratory work and the data analysis, and led the writing of the manuscript.

Publication I was reproduced here by permission of the Baltic Forestry journal, Publication II by Elsevier, Publication III by the Geochronometria journal, Publication IV is an unpublished manuscript.

ABSTRACT

The thesis focuses on the dendrochronological analysis of pedunculate oak (*Quercus robur* L.) in order to investigate the weather impact on its radial increment at its northern distributional limit in Finland and Estonia, and to explain sapwood variability in Finland and the Baltic States (Estonia, Latvia, Lithuania). The first is necessary for past climate reconstruction and the latter is essential for tree-ring dating, since the sapwood is often missing in the datable objects, but the last sapwood ring in the trunk indicates the felling date.

A total of 740 oak tree-ring cores from 47 sites were analysed using traditional dendrochronological methods. The sapwood ring number for the studied region was counted and standardised. The weather-dependent variability in tree-ring width chronologies was studied using correlation and response functions. The feasibility of tree-ring width as a climatic proxy was tested in the palaeoclimatic reconstruction of precipitation using a transfer function.

The research resulted in the first countrywide 366-year-long oak tree-ring chronology (1646–2011) for Estonia and also in three sub-chronologies, as well as respective Finnish, Latvian, Lithuanian chronologies. These show high similarity with the Estonian oak chronology. That similarity extends to northern Poland. However, the similarity between Estonian oaks and conifers is inadequate.

Sapwood ring number within 95% confidence limits varies from 4–21 in southern Finland and western Estonia; 6–18 in eastern Estonia, Latvia and Lithuania; and 6–19 in the eastern Baltic region combined. Regarding earlier studies, the general European trend of decreasing sapwood ring number towards the east was confirmed. A spatial pattern of an eastward decrease in median sapwood ring number was also described within the studied region.

At its northern distributional limit, oak radial growth is limited by summer weather. Accordingly, oaks growing on shallow soil in Finland and western Estonia are positively influenced by summer precipitation. Moreover, sequential summer droughts can be considered to be a potential factor inducing the oak dieback in the studied Finnish forest. On the other hand, the oaks on the deeper soil in northeastern Estonia are favoured by June temperature, while the oaks in the southeastern part of the country depend on July precipitation and temperature. These relationships are especially pronounced in pointer years. In more detail, latewood, which determines the variability in the total annual increment, is affected by similar factors to annual ring width, while earlywood is more influenced by the dormancy period and by spring conditions.

In addition, the research presents the first tree-ring based palaeoclimatic reconstruction for Estonia. The created model has relatively low predictive skill describing less than a quarter of the variance in actual summer precipitation in western Estonia. On the other hand, the pointer years identified in the retrodiction fairly agree with the summer precipitation extremes reported in

historic sources. Thus the reconstruction model has adequate capacity of detecting past rainfall extremes.

In conclusion, the thesis shows that oak growth in dry habitats mostly depends on summer precipitation. The results also explain the feasibility of tree-ring-based climate reconstruction as well as the increased precision of oak dating in the region.

1. INTRODUCTION

In the context of the dispute that has been underway in society over the recent climatic fluctuations, better knowledge of past climate dynamics is needed in order to predict possible future variations. One way to obtain that knowledge is to study trees, which are known to record environmental conditions in their annual growth layers – more precisely tree rings.

In the broadest sense, dendrochronology is a discipline that examines datable tree rings and their variations in relation to environmental conditions such as temperature, precipitation, flooding, landslides, pollution, fire, insect outbreaks etc. In the strictest sense, it is a method that uses tree rings for dating wood (Kaennel and Schweingruber 1995; Speer 2010). Thus, dendrochronology, i.e. tree-ring analysis, serves the dual tasks of long-term environmental monitoring and absolute dating.

Dendroclimatology is one of the first and most applied subfields in dendrochronology – it is a discipline that utilises dated tree rings to reconstruct and study the past and the present climate (Fritts 1976). Palaeoclimatic information can, for instance, also be derived from ice cores, lake and ocean sediments, boreholes, speleothems, but the advantage of tree rings is their annual resolution on the absolute time scale. One disadvantage, however, is the relatively short time span of the data it provides. Only a few chronologies covering the Holocene exist. For example, the Hohenheim oak chronology from Germany reaches back to 8480 BC, and combined with pine, back to 10 461 BC, which gives a 12 460-year long period from AD 2000 (Friedrich et al. 2004), and the Belfast oak chronology starts from 5289 BC (Pilcher et al. 1984; Brown et al. 1986).

1.1. Concept of dendrochronology

The tree ring as the annual growth layer of woody plants is central to dendrochronology. According to Kozlowski (1971), during the annual cambial activity in the zone between the wood and the bark, the processes of cell division, enlargement and differentiation into the phloem and the xylem occur. The xylem is produced towards the inside of the tree and becomes the wood, while the phloem is produced towards the outside of the tree and becomes the bark. At the beginning of the growing season the xylem cells are larger and thin-walled and are defined as earlywood, while cells formed towards the end of the growing season are small, thick-walled and dense and are defined as latewood. These two parts of wood comprise the annual ring. Different rings are distinguishable due to an observable and abrupt change in cell size, i.e. the boundary between one year's latewood and the next year's earlywood in the stem cross-section. Generally, most gymnosperms and woody dicotyledonous angiosperms in seasonal climates produce one tree-ring per year (Speer 2010).

The annual variability in tree-ring volume, wood density or its isotopic composition depends on the environmental conditions under which the rings are formed. Climate is considered to be the most important factor controlling growth at the largest spatial scale (Fritts 1976). There are, however, intrinsic age and size-related growth trends, and also several internal and external stand disturbances that can determine the tree increment (Cook 1990). Similar conditions in a certain area create a similar regional growth pattern. Thus the basic tenet in dendrochronology is the matching (i.e. synchronising, cross-dating) of the inter-annual growth pattern among all investigated radii within a stem, among several trees within one stand, and among a dataset of samples within neighbouring stands (Fritts 1976). Such a chronology of living trees can be cross-dated against progressively older trees, construction timber and megafossils from sediments in the region, and thus extended into the distant past in annual resolution. Regional chronologies can be compared to annual phenomena such as weather records, and used for pre-instrumental palaeo-reconstruction (e.g. Helama et al. 2002; McCarroll et al. 2013); for the determination of the precise year of some environmental event (e.g. Briffa et al. 1998; Corona et al. 2013) or for dating buildings and wooden artefacts (e.g. Pearson et al. 2012; Domínguez-Delmás et al. 2013; Morales et al. 2013), to name but a few applications.

1.2. Distribution of pedunculate oak

According to Fritts (1976), ecological amplitude is the range of habitat over which a species may grow and reproduce. At the centre of its geographical distribution, a tree species is less stressed and climatic factors rarely limit growth, while near the ecological margin it is more stressed and climate limits its physiological processes. Accordingly, for climate-related research it is better to study the tree species near the edge of its range (Speer 2010).

Pedunculate oak (*Quercus robur* L.) is widely distributed throughout Europe, extending from Ireland to the Ural Mts. and from southern Italy to the southern edge of Fennoscandia (e.g. Meusel et al. 1965; Axelrod 1983; Dahl 1998; Fig. 1).

Radiocarbon-dated pollen diagrams show that oak arrived in Estonia between 8700 and 8300 cal BP and spread between 7600 and 4500 cal BP, with its maximum between 4700 and 3300 cal BP (Saarse and Veski 2001; Brewer et al. 2002). Afterwards, oak forests declined due to climate cooling and increasing competition with spruce around 3200 cal BP (Saarse et al. 1999). Clearances for agriculture and grazing further devastated the oak forests (Laasimer 1965). Timber felling for the Imperial Russian shipbuilding industry without subsequent regeneration destroyed the rest of the oak stands during the 18th century (Daniel 1929). Today oak is the dominant tree species in only ca 0.3% of forested areas in Estonia and Latvia (Gailis and Šmaukstelis 1998;

Metsakaitse- ja Metsauuenduskeskus 2009), and in 2% of the forests of Lithuania (State Forest Survey Service 2009).

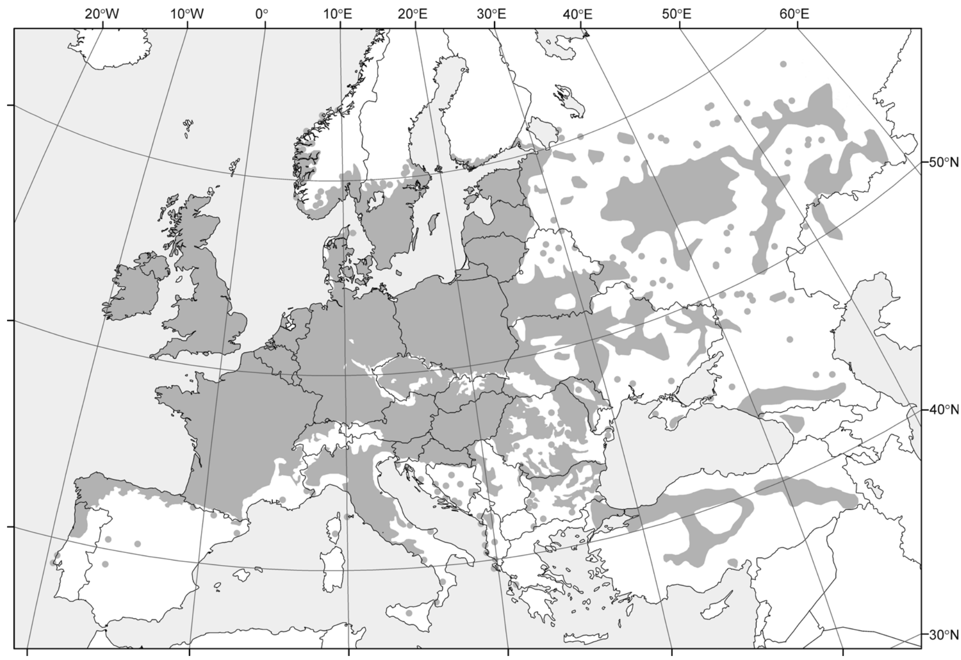

Figure 1. Distribution of pedunculate oak (*Quercus robur* L.) (EUFORGEN 2009).

Pedunculate oak is the only natural oak species in Finland and in the Baltic States, as sessile oak (*Q. petraea* (Matt.) Liebl.) has not reached this far north, except for the southernmost parts of Lithuania (Csaikl et al. 2002). It is known that sessile oak is more sensitive to low average temperatures during the growing season, while pedunculate oak is resistant to winter cold and has a greater water and nutrient requirement, and is more sensitive to drought stress (Lévy et al. 1992; Führer 1998). However, dendrochronologists treat these two oak species as one, as they are wood-anatomically indistinguishable, and hybridization is widespread (Schweingruber 1993). Due to its long lifespan, distinct tree rings, high natural durability and strength, and a broad historic wood use, oak is one of the most investigated tree genera in the European dendrochronology (e.g. Eckstein 1983; Čufar 2007; Haneca et al. 2009).

1.3. Missing sapwood estimations in tree-ring dating

The oak wood in a trunk can be divided into two parts – heartwood and sapwood. Heartwood is the darker inner layer of the xylem in the stem that has ceased to contain living parenchyma cells. Its vessels are plugged with tyloses to stop water conduct, and cells are filled with substances to make the wood resist decay. Sapwood is the lighter coloured outer layer of the xylem which contains living parenchyma cells with a food reserve (e.g. Kaennel and Schweingruber 1995; Speer 2010). As moister sapwood is more vulnerable to decay than solid heartwood, the former is often damaged or uncountable in archaeological samples or trimmed off in the woodworking. However, the number of sapwood rings is necessary for the precise dating of wooden objects, as the last sapwood ring under the bark points to the felling date.

Therefore the number of sapwood rings in living trees and historic timber must be examined to estimate the number of missing sapwood rings in the dating objects. The oak sapwood number has been widely investigated, and statistics for different regions of Europe have been published (Haneca et al. 2009; Table 1). Usually the minimum and the maximum number of sapwood rings within 95% confidence limits are given. In general, the frequency distribution of the sapwood rings is positively skewed, which means that there are more lower values than higher ones (Hughes et al. 1981).

Table 1. Sapwood ring number estimates of oaks in Europe (adapted with modifications from Haneca et al. 2009).

Region	Absolute range	Average/ median*	95%/90%* confidence interval	Source
British Isles	14–66	31.7	15.59–58.15	Hillam et al. 1987
Ireland	14–62	31.3	16.74–53.93	Baillie 1982
NW England and N Wales	10–55	25.8	13.7–44.6	Hughes et al. 1981
N England	10–60	–	12–45	Miles 1997
S England	4–57	–	9–41	Miles 1997
Wales and border counties	8–50	–	11–41	Miles 1997
N France	12–49	26.6	15.25–43.26	Pilcher 1987
Belgium	13–39	24.5	11.54–37.42	Haneca et al. 2009
Italy	5–38	13.2	5.66–30.93	Martinelli pers. comm. cit. Haneca et al. 2009
Germany	7–66	19	8.22–37.95	Hollstein 1965, 1980
N Germany	–	–	10–30*	Wrobel and Eckstein 1993
S Moravia	5–21	–	–	Rybníček et al. 2006
Hungary	7–36	16.6	–	Grynaeus 1998
Poland	6–31	16	9–24*	Ważny 1990
N Poland	9–36	15*	11–23*	Klein 2006
W Sweden	9–32	15.8	8.73–26.55	Bräthen 1982
S Finland	7–24	13.9	–	Baillie et al. 1985

Sapwood volume can vary greatly both within and between individual trees at any particular site (Hughes et al. 1981). The amount of sapwood within a trunk increases with the sampling height. The cross-section of the tree trunk may also exhibit significant variation. Sapwood can also increase with the age of a tree and with a falling growth rate, i.e. old or slow-growing trees have more sapwood rings than younger or faster-growing ones (e.g. Hughes et al. 1981; Hillam et al. 1987; Wrobel and Eckstein 1993). However, models describing the relationship between the age or mean ring width of the tree and number of sapwood rings have low predictive skill (Hughes et al. 1981; Baillie 1982; Hillam et al. 1987). It is assumed that the amount of sapwood has remained constant for oak populations throughout history, although some archaeological oak artefacts have shown considerably greater or smaller sapwood numbers than modern timber (Grynaeus 2003; Randsborg and Christensen 2006).

Sapwood estimates from different regions have revealed a tendency towards decreasing sapwood numbers moving from west to east within Europe (Table 1). There may also be a north–south trend based on the material from the British Isles (Hillam et al. 1987). This is a potential problem of interpretation regarding the tree-ring dates of imported timbers (Baillie et al. 1985). Accordingly, the amount of sapwood in different regions is relevant in the context of the historical timber trade. Based on historic data and dendro-provenancing research, the export of oak timber from Baltic ports to Western Europe from the 13th century to the mid-19th century has been established (e.g. Baillie et al. 1985; Eckstein et al. 1986; Ważny and Eckstein 1987; Bonde et al. 1997; Zunde 1998–1999; Ważny 1992, 2002, 2005; Haneca et al. 2005). Generally a large quantity of oak was transported via the eastern Baltic ports of Danzig (Gdańsk), Königsberg (Kaliningrad), Memel (Klaipeda), Libau (Liepāja) and Riga to Western Europe (Bonde et al. 1997; Zunde 1998–1999; Kremser 1998). Its original sources were mainly the catchments of the Vistula, Neman and Daugava rivers, as well as the Dnieper basin, which are now parts of Poland, Ukraine, Belarus, Russia, Lithuania, and Latvia. The largest quantity of timber was exported through Danzig until the end of the 16th century, when the Baltic timber trade shifted towards the Couronian ports and Riga in the north (Zunde 1998–1999; Ważny 2005). The centre of the timber trade from Russian territory close to Lake Peipus was Narva in Estonia, and this trade peaked in the second half of the 17th century (Soom 1940; Kremser 1998) and was active until at least the second half of the 18th century (Hupel 1777; Eckstein and Wrobel 2007). Hence, the dating of the imported historical timber in Western Europe requires sapwood estimates from the regions from which the wood originates. Prior to the present work, no estimation of oak sapwood rings for the Baltic States existed.

1.4. Dendroclimatic signals of pedunculate oak

The dendroclimatic signal of oak as disclosed by its tree-ring widths varies greatly across Central Europe. Moreover, the main two factors, temperature and precipitation, appear to be inconsistently connected to oak growth, both temporally and spatially (e.g. Eckstein and Schmidt 1974). Thus conventional dendroclimatology does not work throughout Europe in the same way.

Nevertheless, it can be stated that during a wet and warm growing season a tree develops a considerably wider ring, and vice versa in Western Europe (Pilcher and Gray 1982; Bridge et al. 1996; Lebourgeois et al. 2004; Friedrichs et al. 2009). In the Southern Europe, however, temperature has an opposite response. In Slovenia, for example, where the Alpine, Mediterranean and continental climates meet, June rainfall has a positive effect and temperature has a negative effect on ring width (Čufar et al. 2008a, 2008b). The same has been widely described in the Mediterranean environments (Santini et al. 1994; Tessier et al. 1994) and Atlantic Spain (Rozas 2001, 2005) where high precipitation creates favourable growth conditions and high temperature leads to unfavourable conditions during the summer period. On a contrary note, water excess can be limiting for growth and may trigger forest dieback in rainy temperate deciduous forest (Rozas and García González 2012a). An enhancing precipitation effect has also been widely observed in Eastern Europe (Bednarz and Ptak 1990; Ważny and Eckstein 1991; Askeyev et al. 2005; Cedro 2007; Bronisz et al. 2012). Even at oak's northern border in southern Fennoscandia, poor growth has mainly been ascribed to a deficit of water (Drobyshev et al. 2008; Helama et al. 2009; Hilasvuori and Berninger 2010).

In addition to the current growing season, oak tree-rings may correlate with the weather characteristics of the previous year (Pilcher and Gray 1982; Drobyshev et al. 2008; Helama et al. 2009). More specifically, earlywood growth may be positively associated with the preceding year's latewood width and the temperatures of the previous autumn and winter, while latewood growth is related to precipitation in the the current growing season (Eckstein and Schmidt 1974; Nola 1996; Doležal et al. 2010).

1.5. Previous dendrochronological studies in Finland and the Baltic States

Finland, the second most forested country in Europe, has a long tradition of dendrochronological studies. Early research by Laitakari (1920) on the relationship between Scots pine (*Pinus sylvestris* L.) growth and the weather has been followed by numerous studies about the growth variations of conifers in forestry and also on the effect of climate fluctuation on trees (Mikola 1956). The country's geographical location has given it a good potential to study pine growth at the northern forest-limit in Finnish Lapland. During recent decades this work has resulted in the multi-millennial long chronologies and palaeoclimatic reconstructions (e.g. Lindholm and Eronen 2000; Eronen et al. 2002; Helama et al. 2002). Oak growth at its northern distributional range has been studied in the context of both forest decline (Helama et al. 2009) and stable isotope abundances (Hilasvuori and Berninger 2010).

The Dendroclimatochronological Laboratory established by Teodoras Bitvinskas in Kaunas in 1968 was the main tree-ring research facility in the USSR (Bitvinskas 1998). Today a great variety of dendroecological and climatologial conifer studies have been carried out in Latvia and Lithuania (e.g. Vitas 2004; Vitas and Erlickytė 2007; Zunde et al. 2008; Baltrėnas and Vaitkutė 2011; Dauškane and Elferts 2011). Oak's responses to weather variables (Ruseckas 2006; Matisons and Brūmelis 2012; Matisons et al. 2012, 2013) and subfossil oak as a historical vegetation indicator (Pukienė 2003) have also been under investigation. In addition, excavated oak timber from the Lower Castle of Vilnius has been dated (Pukienė and Ožalas 2007), and floating oak chronologies from Latvia and Lithuania have been created (Vitas and Zunde 2008).

As dendrochronology itself deals with the environment as well as with the dating of wooden objects, both directions have also found their place in Estonian tree-ring research. In the early 1970s architect Kalvi Aluve made his first attempts in the field of dendrochronology by dating the historical buildings in western Estonia (Aluve 1978). At approximately the same time, Alar Läänelaid began with pines growing on raised bogs (Läänelaid 1979) and with tree-ring dating, creating a network of dated tree-ring series of living trees and also of buildings and archaeological wood all over Estonia (Läänelaid 2002). During the 1970s and1980s forest ecologist Erich Lõhmus compiled pine chronologies for dry, wet and well-drained sites (Lõhmus 1992). Today Rivo Bernotas has continued by dating archaeological samples (Bernotas 2008). As Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) H. Karst.) are the main construction woods in Estonia, chronologies of these species have been extended into the past, and growth responses to climatic factors have been examined (e.g. Läänelaid and Eckstein 2003, 2012; Läänelaid et al. 2012). Hence the pine chronology extends back to the start of the 12th century and the spruce chronology goes back to the 16th century (Läänelaid 2012). Studies on introduced larches (*Larix* spp.) are in progress (Sander and Läänelaid 2007). In addition, dendroecological studies exploring the impact of air pollution on conifer growth in industrial areas have been carried out (e.g. Pärn 2003, 2006), and applications of dendroclimatological methods have been used for forest growth modelling (Hordo 2011).

Thus the different dendrochronological aspects of conifers have been studied widely in Estonia, while less attention has been paid to deciduous trees. Prior to this thesis, only the age of large outstanding oaks and limes in parks had been examined (e.g. Läänelaid et al. 2001; Sander et al. 2008). Although there is experience of dating oak panels as well (e.g. Läänelaid and Nurkse 2006), the dated wood probably originates from further south, and the Baltic oak reference chronology (Hillam and Tyers 1995) has been used.

1.6. Objectives

Based on the aforementioned dendroclimatological and tree-ring dating aspects, the main objective of this thesis was to investigate the dendrochronological and dendroclimatic potential of oak at its northern distributional limit in Europe, particularly in Finland and the Baltic States (Estonia, Latvia, Lithuania), with a further focus on oaks growing in Estonia. The specific tasks to be fulfilled were as follows:

1) to construct a network of oak tree-ring width chronologies for Estonia (Publications I and IV);
2) to assess the similarity of Estonian oak chronology with adjacent regions (teleconnection) and with the conifers in Estonia (heteroconnection) (Publication II and IV);
3) to describe and standardise the variability of the oak sapwood rings in the eastern Baltic Sea region, i.e. in Finland, Estonia, Latvia, and Lithuania (Publication II);
4) to detect climatic factors affecting oak growth in Finland and Estonia, both on an annual (Publications I, III and IV) and on a seasonal scale (Publication III);
5) to explore the potential of oak tree-ring width as a climatic proxy in Estonia (Publication IV).

2. MATERIAL AND METHODS

2.1. Tree-ring data

Altogether, 740 oak tree-ring cores from 47 sites in Finland, Estonia, Latvia and Lithuania were used in the analysis (Fig. 2). 162 cores from 12 sites in Estonia and 30 cores from one site in Finland were investigated in the dendro-climatological analyses (Publications I, III, IV), and 668 cores from 43 sites in Finland and the Baltic States were examined in the sapwood analysis (Publication II). These datasets partially overlapped.

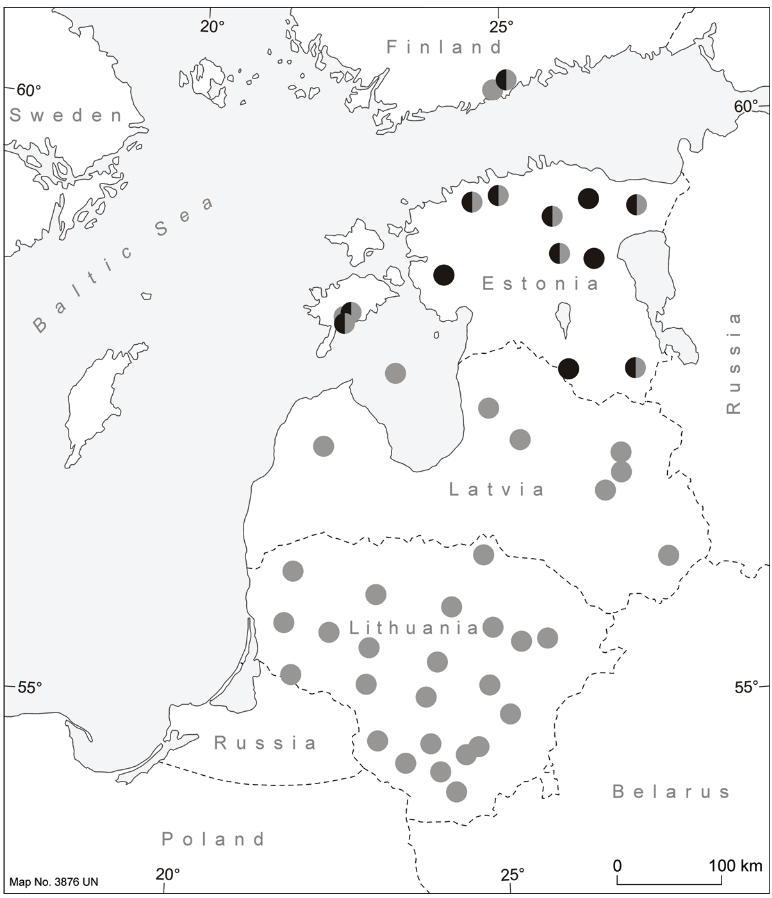

Figure 2. The 47 study sites in Finland, Estonia, Latvia, and Lithuania. Grey dots indicate the oak tree-ring data for the sapwood analysis, black dots data for the dendroclimatic analysis, and mixed-colour dots indicate overlapped datasets.

The fieldwork was carried out in Estonia during the period 1997–2011 (the author led the sampling in Saue, Lehmja, Mäetaguse, Vinni, Rava, Päinurme, Kuremaa, Lasva, Sooru, and participated in the sampling in Loode), in Latvia in 2007 (fully led by the author) and in Finland during the years 2007–2008 (the author participated in the sampling in Tammisto). The author did not work in Lithuania, as these samples originated from the database of the Group of Dendroclimatology and Radiometrics of Vytautas Magnus University (sampled during 1969–1997). The core samples of 5 mm in diameter were taken with a 40 or 50 cm increment borer from a height of between 100–130 cm and preferably from the northern side of the trunk of living trees. Only one core per tree was taken, as the growth pattern of oaks from one stand synchronise well, and missing rings are not common. The aim was to core radially towards the pith. However, owing to the great diameter of the trees, not all core samples had near-pith rings. The perimeter of each tree and the thickness of the bark at the sampling spot were measured. As the mortality of trees was investigated in Tammisto, the declining and dead trees were also included (Publication III). In addition, soil depth in Tammisto was measured to the nearest 1 cm by driving a soil probe into the ground until refusal around each cored tree from four directions, at a distance of two meters from the stem (Publication III).

The dried sample cross-section surfaces were planed with a razor blade in the dendrolaboratory in order to sharpen the visibility of the tree-ring pattern. As followed, the tree-ring widths (Publications I, II, IV) and the early- and latewood widths separately (Publication III) were measured to the nearest 0.01 mm on a Lintab measuring table (Heidelberg, Germany) equipped with an incident light microscope (Fig. 3). The boundary between the early- and latewood was distinguished according to a qualitative aspect: the earlywood contains the large vessel zone, while the latewood has the small cell zone (e.g. Schweingruber 2007). The sum of the early- and latewood measurements was adopted as the total annual ring width. The measured values were recorded and the graphs displayed with the TSAP-Win software (Rinn 2003). The measurement quality was controlled visually from the graphs, and using the COFECHA software by the Dendrochronology Program Library (DPL) (Holmes 1983).

In order to compare the measurements, different tree-ring statistics were calculated, for example average tree-ring width, standard deviation, relative growth rate (Briffa and Melvin 2011; Helama et al. 2012; Eq. 1 in Publication III), and mean sensitivity (Fritts 1976; Eq. 2 in Publication III).

As the coring date was known, the last annual ring of living oaks could be coupled with the calendar year of sampling. The samples from the declining and dead trees (Publication III) were cross-dated against the mean series of living trees using the dendrochronological program CATRAS (Aniol 1983), and the dating results were visually checked from graphs.

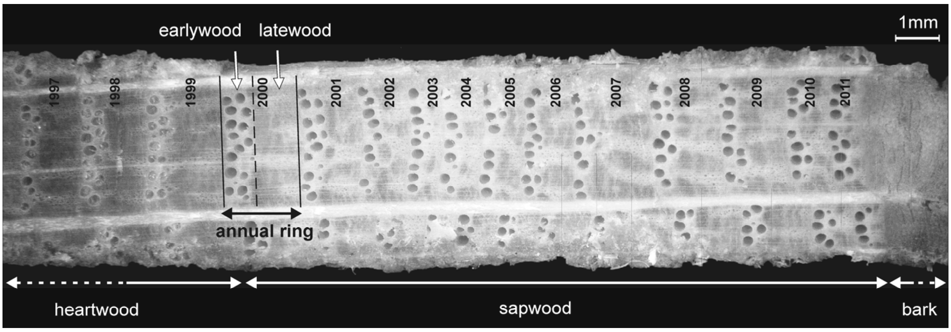

Figure 3. A fragment of a core sample: the lighter sapwood without tyloses in the lumina under the bark followed by the darker heartwood with tyloses in the lumina. An annual ring consists of earlywood with large vessels and of latewood with small dense cells.

To reveal the long-term growth pattern, the average series of tree-ring data were also created according to their biological, i.e. cambial age (e.g. Briffa et al. 1992), where the rings were aligned by their age, starting from the pith instead of the calendar years (Publication III). To estimate the age of the large trees (Publication I), the cumulative increment method was used (e.g. Läänelaid et al. 2001).

In order to assess teleconnection, i.e. similarity between the chronologies from distant sites (Kaennel and Schweingruber 1995), the studied tree-ring data were compared with Finnish (Helama et al. 2009) and Polish (Ważny and Eckstein 1991; data provided by the NOAA International Tree-Ring Data Bank, www.ncdc.noaa.gov/paleo/treering.html; Koprowski and Murawska unpublished) regional reference chronologies (Publications II and IV). The heteroconnection, i.e. similarity between the chronologies of different tree species from the same area (e.g. Čufar et al. 2008b), was observed between the Estonian oak chronology and the local pine (Läänelaid et al. 2012) and spruce chronologies (Läänelaid 2012) (Publication IV).

2.2. Computation of chronologies

As raw tree-ring series contain different short- and long-term trends, these are detrended and averaged into site chronologies, i.e. the standardization procedure (Fritts 1976) is applied. Accordingly, here the measurement series were detrended using a negative exponential curve or/and spline function (Cook and Peters 1981) in order to remove the tree-age-related growth trend and to reduce non-climatic noise (i.e. low-frequency noise). A curve was fitted individually to each tree-ring width series, and dimensionless indices were derived from the curve by division. Thus this process also removed the differences in growth rates between the samples. For the dendroclimatological analysis (Publications I, III, IV), the index series were further pre-whitened to remove persistence due to autocorrelation. Pre-whitening transforms autocorrelated series into a series of independent observations by extracting residuals from the modelled process. A chronology free of autocorrelation is called a 'residual chronology' (Publications I, III, IV), and a chronology retaining autocorrelation is called a 'standard chronology' (Publication II). Finally, the index series were averaged using a bi-weight robust mean estimation to reduce outlier effects (Cook et al. 1990). Technically, the tree-ring width series were standardized into site chronologies using the CRONOL (DPL, routine CRN) (Publications II and IV) or/and ARSTAN software (Cook 1985) (Publications I, III, IV). Simple unstandardized average chronologies computed in the TSAP-Win software were also used here.

To determine the adequacy of the sample size for the dendroclimatological analysis, the expressed population signal (Publication I) or subsample signal strength (Publication IV) (Wigley et al. 1984) was calculated by ARSTAN. In Publication III the time range that contained at least five trees in subset was considered representative (Läänelaid 2000).

The similarities between the site chronologies were assessed using the following statistics in the TSAP-Win software (Rinn 2003): the *Gleichläufigkeit* (GLK) (Eckstein and Bauch 1969), and Baillie-Pilcher's t-value (t_{BP}) (Baillie and Pilcher 1973) (Publication IV) or Hollstein's t-value (t_H) (Hollstein 1980) (Publication II). t-values ≥ 3.5 or ≥ 4 were considered significant (e.g. Baillie and Pilcher 1973).

In order to group the site chronologies, a principal component analysis (PCA) was carried out using the STATISTICA 7 software package (Publication IV), or groups were made arbitrarily according to similarities between the chronologies and regarding geobotanical zones (Sochava et al. 1960; Laasimer 1965) (Publication II).

2.3. Sapwood estimation

Only cores with complete rings under their bark were used in sapwood analysis (Publication II). Two boundaries between the sapwood and the heartwood were determined – according to the colour difference and the presence or absence of tyloses in the earlywood vessels (Fig. 3). The number of sapwood rings was counted under the microscope. The distributions of regional sapwood datasets were tested for normality, and in the case of asymmetry the data were transformed in the STATISTICA 7 software package. Subsequently, the mean, median, minimum, maximum and 95% interval of expected values were calculated for the normally distributed series.

In addition, a regression model was used to identify the relationship between sapwood number by colour and mean ring width. The spatial variation of the median sapwood values between the individual sites was also observed. Thus the sapwood data by the colour criterion were divided into three classes such that the middle class comprised the median value ± 1 ring. Linear regression models were used to describe the relationships between the sapwood ring number and the longitude, and also the latitude.

2.4. Meteorological data

The tree-ring chronologies were compared with the data from the nearest available meteorological station provided by the Estonian Meteorological and Hydrological Institute (EMHI) (Publications I and IV) and by the Finnish Meteorological Institute (Publication III). Specifically, monthly mean temperature and precipitation (Publications I and III); monthly mean temperature, monthly minimum temperature in April, May, June, and monthly precipitation as interpolated for the sites based on the four closest stations were used (Publication IV). In addition, monthly North Atlantic Oscillation (NAO) indices (Hurrell 1995; NAO Index Data provided by the Climate Analysis Section, NCAR, Boulder, USA, http://climatedataguide.ucar.edu/guidance/hurrell-north-atlantic-oscillation-nao-index-station-based) were used (Publication IV).

2.5. Dendroclimatological data analysis

The relationships between tree-ring data and the meteorological data were examined using correlation and response functions. Bootstrapped confidence intervals were used to estimate the significance of Pearson's correlation and response function coefficients ($p<0.05$). In response functions, the coefficients are multivariate estimates from a principal component regression model (Briffa and Cook 1990). A 15-month window from the previous July (Publication I) and a 12-month window from the previous October through to September of the current year were used (Publications III and IV). The relationship dynamics with the NAO index series were calculated using moving 60-year intervals (Publication IV). Relationship dynamics with the meteorological data were tested using 36-year intervals (Publication I). Technically, these analyses were run in the DendroClim2002 program (Biondi and Waikul 2004). In addition, three-monthly seasonal average temperatures and precipitation sums from the previous September to the concurrent August were calculated and correlated with the tree-ring chronologies (Publication III). The effect of frosts at the beginning of the vegetation period was investigated through Spearman's rank correlation (ρ) between the tree-ring data and the monthly minimum temperature of April, May, and June (Publication IV).

In addition, pointer years which indicate years with conspicuous features such as exceptionally narrow or wide rings within a group of trees (Schweingruber et al. 1990; Kaennel and Schweingruber 1995) were identified to determine extreme growth fluctuations (Publications I and IV). The combined criteria of pointer interval and pointer value were used. In Publication IV, pointer interval corresponded to the year during which the growth of at least 75% of the trees showed the same upward or downward trend from the previous year. The pointer value corresponded to a year with an exceptionally narrow or wide ring of at least 50% of trees using a moving 5-year window. In Publication I, thresholds of 70% and 55%, a moving 7-year window, respectively, were used. Technically, the pointer years were calculated from the raw tree-ring series in the Weiser program (García González 2001). The weather-growth relationships within the pointer years were quantified using Spearman's rank correlation (Publication IV).

Based on the results of the response analysis, the most important weather variable for tree growth was chosen for the historical reconstruction (Publication IV). The tree-ring data served as the predictor and the climatic data as the predictand variable in a transfer function (Fritts 1976). The whole process of obtaining a useful transfer function to estimate the dependant climatic variable from the independent tree-ring data is termed 'calibration'. Here a simple linear regression was used. In order to test the reliability of the model, a cross-calibration/verification procedure (e.g. Briffa et al. 1988a) was adopted. First, the full overlap period between the tree-ring set and the instrumental weather data was divided into two subperiods. The early period was used for the calibration and the late period for the verification, and vice versa. The retrodiction was verified using statistics such as reduction of error (RE), coefficient of efficiency (CE), and the first difference sign test (e.g. Fritts 1976; Briffa et al. 1988a; Fritts et al. 1990). Eventually, the reconstruction equation was recalibrated using the entire overlap period. In the new tree-ring based palaeoclimatic reconstruction, two classes of positive and negative deviations from the mean were determined. The reconstructed values outside the mean ± 1.28 SD referred to the years with 'strong' weather conditions, and values outside the mean ± 1.645 SD referred to the years with 'extreme' weather conditions (Neuwirth et al. 2007; Čufar et al. 2008a). Finally, the 'strong' and 'extreme' years in the reconstructed time series were validated with the extraordinary weather events in Estonia from 1713–1870, as compiled from several historical sources by Vahtre (1970), in addition to the instrumentally recorded data from the EMHI.

3. RESULTS AND DISCUSSION

3.1. Site chronologies

Most of the core samples represented living trees (except for the dead and declining trees from Tammisto; Publication III), and covered the years 1631–2011 (Fig. 4). The median number of tree-ring samples was 114 (minimum and maximum accordingly 29 and 183) in Finland, 141 (48 and 375) in Estonia, 154 (58 and 195) in Latvia, 128 (50 and 242) in Lithuania. The minimum ring count was low mostly due to rotten hearts or broken samples. Thus the ring count did not accurately show the age of trees. The oldest oaks grew on Saaremaa Island and contained up to 375 annual rings. According to the method of cumulative increment and fitting the polynomial growth trend, the oldest trees could be estimated to be five hundred years old in the Loode forest on Saaremaa Island (Fig. 2 in Publication I). This is possible, since the Loode forest has been used as a wooded hayfield and pastureland for centuries (Meikar 2008).

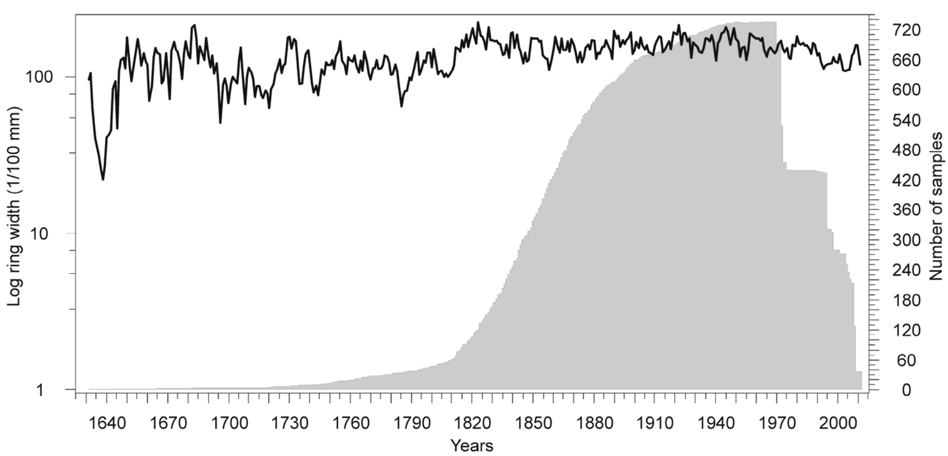

Figure 4. The average oak chronology of 740 trees from Finland and the Baltic States (black line), and the sample size (grey bars).

According to the similarity statistics between the sites, the most homogeneous group of oaks grew in Lithuania (Table 1 in Publication II), while there was a weaker similarity across Estonia or across Latvia (Table 2 in Publication II). However, the Estonian and Latvian chronologies were still more similar to each other on the intra-country rather than the inter-country level. As the Finnish sites were located close to each other (at a distance of ca 10 km), they showed high similarity based on 10 trees from both stands (Table 2 in Publication II). Increasing the sample replication for up to 30 trees each (Helama et al. 2009; Publication III), the similarity was even higher (GLK = 74.6%; $t_{BP} = 11.3$; overlap 140 years). Thus the closer sites showed higher similarities in their growth pattern.

Further on, the Estonian site chronologies were grouped according to the results of the PCA (Fig. 3 in Publication IV). The PC1 described 43%, the PC2 13%, and the PC3 10% of the variance in the chronologies. The PC1 contained a high amount of common variance throughout the country, and no grouping was feasible. According to the PC2, three geographically logical clusters were distinguished: the western, the northeastern and the southeastern groups. The correlation coefficients between the PCs and the climatic variables revealed that the PC1 could be associated with the countrywide summer (June–August) precipitation (Table 2). This means a common positive relationship between tree-ring width and precipitation, i.e. during the wet growing season considerably wider rings were built than during dry summers. However, the PC2 correlated with the countrywide summer precipitation as well as with summer temperature, i.e. it reflected an effect of drought. Hence drought was more pronounced on the tree-rings in the western sites rather than in the eastern sites. The correlation between summer precipitation and temperature time series was –0.34 ($p < 0.05$). The PC3 reflected the prior winter conditions as it significantly correlated with winter (December, January, February) precipitation in southeastern Estonia and with January temperature in western Estonia ($r = -0.25$; $p < 0.05$; not shown in the Table 2). (It should be emphasised here that the relative signs associated with PCs are arbitrary due to the STATISTICA 7 program, and therefore the signs of the correlation coefficients are meaningless in Table 2 as well. Thus in interpreting the PCs, real data series should be used.)

Accordingly, the oak site chronologies in Estonia hold a high common variance (Fig. 4 in Publication IV). The t_{BP}-values between the simple unstandardized average oak chronologies are shown in Table 3. Moreover, Estonia as a uniform dendrochronological region has also been asserted by pine and spruce data (Läänelaid and Eckstein 2003, 2012). The lowest similarity between the regions was shown by the southeastern oak sites, which can be explained by a larger influence of site-specific factors reflected in the chronologies due to lower sample replication ($n = 21$).

Nevertheless, the mutual signal in Estonian oak chronologies can be attributed to a common trans-regional factor such as summer precipitation. Slight differences between three regions derive from the climatic variance caused by the Baltic Sea, which causes mild winters in western Estonia, leading to higher annual mean temperature. The submaritime climate also means high annual precipitation in the western mainland. The southeastern uplands also receive much rainfall, while the very coastal areas and eastern Estonia are dryer. The differences in precipitation are most pronounced during the warm half of the year. There is a seasonal pattern to these regional differences, as rainfall is higher in southeastern Estonia during the spring and the first half of the summer and lower in the western part, and vice versa during the end of the summer and the autumn (Jaagus 1999). The western and southeastern areas also feature a 10 day longer thermal growing season (with daily mean air temperature permanently above +5°C) than the central and northeastern parts of the country (Eesti Entsüklopeediakirjastus 2005).

Table 2. Pearson correlation coefficients between the three first principal components and three-monthly seasonal precipitation and temperature in western (W Est), northeastern (NE Est), southeastern Estonia (SE Est), and countrywide (Est) during 1934–1997. Statistically significant relationships ($p < 0.05$) are in bold.

Precipitation	PC1	PC2	PC3	Temperature	PC1	PC2	PC3
W Est winter (DJF)	0.21	0.18	–0.22	W Est winter (DJF)	0.00	0.18	–0.16
W Est spring (MAM)	0.09	–0.06	0.16	W Est spring (MAM)	–0.06	0.11	0.09
W Est summer (JJA)	**–0.45**	**0.38**	–0.06	W Est summer (JJA)	–0.16	**–0.35**	0.03
W Est autumn (SON)	–0.03	–0.03	–0.03	W Est autumn (SON)	–0.17	–0.04	–0.06
NE Est winter (DJF)	0.23	0.12	–0.23	NE Est winter (DJF)	0.00	0.18	–0.11
NE Est spring (MAM)	0.02	–0.13	0.05	NE Est spring (MAM)	–0.08	0.06	0.08
NE Est summer (JJA)	**–0.32**	**0.26**	–0.04	NE Est summer (JJA)	–0.19	**–0.30**	0.02
NE Est autumn (SON)	0.02	–0.06	–0.03	NE Est autumn (SON)	–0.18	–0.05	0.02
SE Est winter (DJF)	0.17	0.16	**–0.28**	SE Est winter (DJF)	0.00	0.15	–0.16
SE Est spring (MAM)	0.01	–0.11	–0.21	SE Est spring (MAM)	–0.10	0.05	0.10
SE Est summer (JJA)	**–0.27**	0.24	0.00	SE Est summer (JJA)	–0.18	**–0.29**	0.05
SE Est autumn (SON)	0.11	–0.07	–0.10	SE Est autumn (SON)	–0.14	–0.08	–0.01
Est winter (DJF)	0.17	0.19	–0.23	Est winter (DJF)	0.00	0.17	–0.14
Est spring (MAM)	0.03	–0.09	0.05	Est spring (MAM)	–0.08	0.08	0.09
Est summer (JJA)	**–0.37**	**0.33**	–0.04	Est summer (JJA)	–0.18	**–0.32**	0.03
Est autumn (SON)	0.02	–0.06	–0.05	Est autumn (SON)	–0.17	–0.06	–0.01

Table 3. t_{BP}-values between the average oak chronologies within the maximal possible range. The sample size in chronology (n) is shown in brackets. The Polish data, i.e. the East Pomeranian data by Ważny and Eckstein (1991) come via the NOAA International Tree-Ring Data Bank, and supplementary Finnish data are by Helama et al. (2009).

		1	2	3	4	5	6	7	8
1	Estonia (n = 162)	x							
2	W Estonia (n = 75)	58.4	x						
3	NE Estonia (n = 66)	17.7	8.4	x					
4	SE Estonia (n = 21)	9.2	4.7	4.5	x				
5	Finland (n = 60)	8.3	8.7	6.6	2.5	x			
6	Latvia (n = 81)	8.3	6.0	7.5	5.8	4.4	x		
7	Lithuania (n = 439)	8.8	7.1	5.8	3.9	4.1	10.7	x	
8	N Poland (n = 205)	6.6	6.3	3.3	1.1	3.3	3.7	7.9	x

3.2. Teleconnection and heteroconnection between the chronologies

Teleconnection is the similarity between time series from distant sites (Kaennel and Schweingruber 1995). Synchronisation between the tree-ring series decreases with distance (Schweingruber 1996). As a growth pattern depends on environmental conditions, presumably mostly on the climate under which the rings are formed, then teleconnection is an indirect measure of the common climatic signal. There is a strong teleconnection between the oak chronologies in different parts of Europe. For instance, the southeastern Slovenian oak chronology shows a significant similarity with regional and local chronologies up to 700 km away in eastern Austria, Hungary, Serbia, the Czech Republic and southern Germany (Čufar et al. 2008b). Kolář et al. (2012) have demonstrated the high resemblance of the Czech oak chronology with the chronologies of eastern Austria, Germany, the Polish part of South Silesia, and even further locations in the Low Countries, France, Switzerland, Romania, Slovenia, and Hungary. The oak chronologies from coastal Poland synchronise well with the chronologies from the southern Baltic region including Sweden, Denmark and northern Germany, but also Lithuania (Ważny and Eckstein 1991). Moreover, Kelly et al. (2002) have shown common signature years (i.e. extremely wide and narrow rings) in the Northern European oak chronology, which are associated with the Arctic Oscillation and its influence upon the westerly airflows across northwestern Europe.

Here, the similarity between the adjacent regional chronologies was described by the t_{BP}-values (Table 3; Fig. 5; Fig. 5 in Publication IV). The former two sources represent simple unstandardized average chronologies, while the latter shows the similarities between the standardized chronologies. The differences between these t_{BP}-values were, however, negligible. As a result, the regional tree-ring pattern in Estonia uniformly resembled (t_{BP} around 8) the Finnish, Latvian and Lithuanian oak growth patterns. Moreover, the importance of spatial distance was evident, as the Finnish oaks most closely resembled Estonian oaks rather than those of southern regions. Specifically, the southern Estonian oaks exhibited the weakest similarity to those of neighbouring regions, which could be explained by the aforementioned low sample depth and, thereby, probably site-specific factors that remained in chronologies. On the other hand, only the growth pattern of the western Estonian oaks was similar to the northern Polish oaks. Both of these are Baltic coastal areas with a sub-Atlantic climate. At the same time, the chronology of eastern Estonian, Latvian and Lithuanian oaks showed a closer correspondence with other northern and eastern Polish sites (Publication II), which can be explained by the large proportion of the adjacent Lithuanian trees in the chronology.

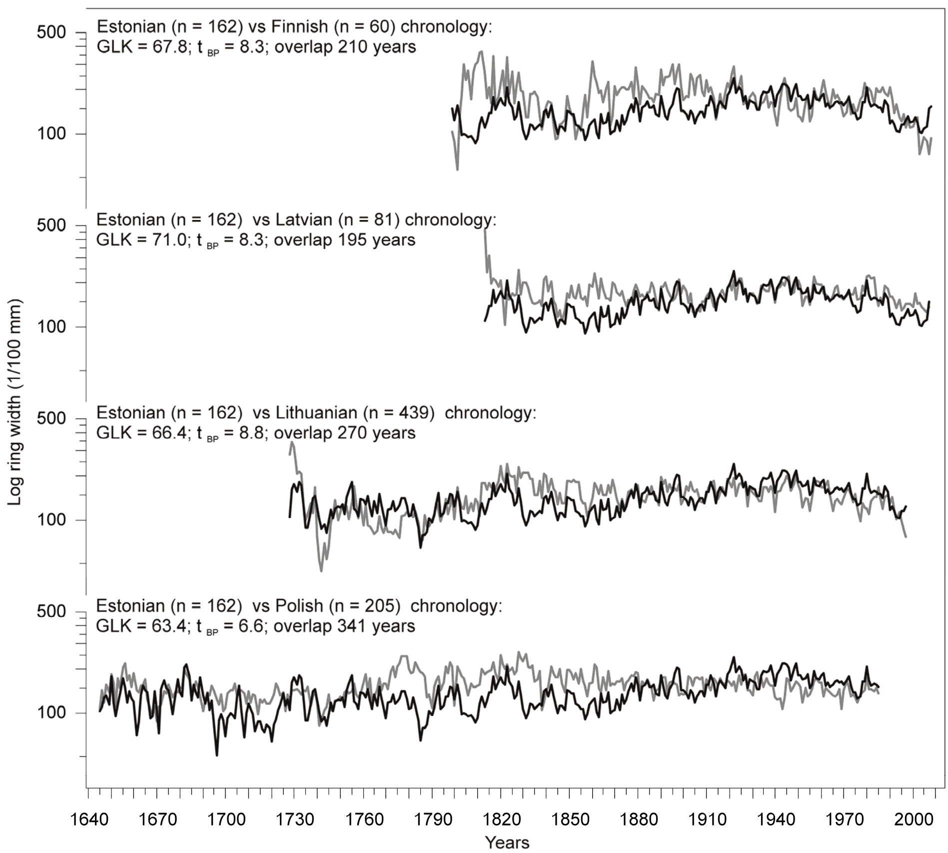

Figure 5. The Estonian average oak chronology (black line) set against the chronologies of the neighbouring regions (grey lines), and the cross-dating statistics within the maximal possible range. The sample size of a chronology (n) is shown in brackets. The Polish, i.e. East Pomeranian data by Ważny and Eckstein (1991) come via the NOAA International Tree-Ring Data Bank, and supplementary Finnish data is provided by Helama et al. (2009).

In addition, a similarity within a shorter common time interval (1910–1985) was observed. As a result, all t_{BP}-values dropped somewhat, but most significantly between the Estonian and the Polish data sets. Across centuries, these two time series resulted in the best synchronisation during the 17th and 19th centuries. Thus northern Poland is the southern limit of the region in which some similarity with Estonian oaks can be established (the distance between them being approximately 500 km). For example, there is no remarkable similarity further south between the Czech and the Estonian or the eastern Baltic chronology (Kolář et al. 2012). On the other hand, the accordance between chronologies across the west to east gradient was not studied here. Thus there is a prospect for further studying oak teleconnection in the future. Some matching towards the east can be assumed, i.e. the northeastern and/or the southeastern chronology with the Russian one, and towards the west, i.e. the western chronology with the Swedish one.

According to the previous tree-ring studies of pine wood, Estonia belongs to the Baltic Sea dendrochronological region (Läänelaid 2001; Läänelaid et al. 2012). However, the Estonian pine chronologies show a better agreement with the western (Swedish) chronologies than with the northern (Finnish) and the southern (Latvian, Polish) chronologies.

Like teleconnection, the similarity between the chronologies of different tree species from the same area, i.e. heteroconnection (e.g. Čufar et al. 2008b), expands the applications of dendrochronological dating. For instance, Čufar et al. (2008b) have shown a significant agreement between oak and ash, beech and even fir chronologies, and Domínguez-Delmás et al. (2013) have done so between oak and chestnut from the same region. All of this is possible if the growth of different species has been determined by the same weather conditions. Here the heteroconnection between Estonian oak chronology and the local pine (Läänelaid et al. 2012) and spruce chronologies (Läänelaid 2012) were observed (Publication IV). Even if it has been possible to date the spruce wood against the pine chronologies in some cases (Läänelaid 2002), no significant accordance between oak and the conifers were detected (Fig. 6). The t_{BP}-value between the oak and pine chronologies was 2.9 and between oak and spruce 2.0, while pine and spruce showed an agreement at the level of 9.2, all within the period 1645–2006. This leads to the fact that different species are affected by different weather conditions in the region.

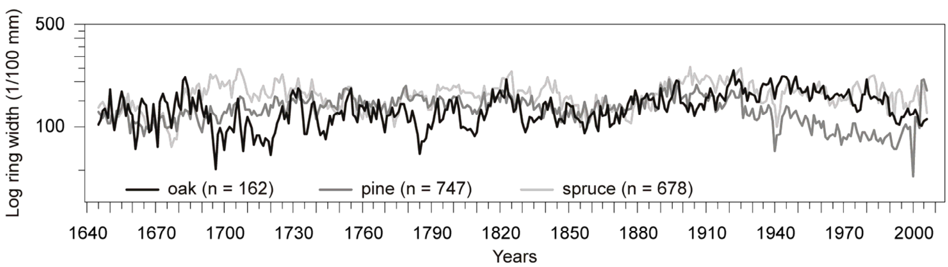

Figure 6. The Estonian average oak chronology (black line) set against the Estonian average pine (dark grey line) (Läänelaid et al. 2012) and spruce chronologies (light grey line) (Läänelaid 2012). The sample size in the chronology (n) is shown in brackets.

The regional oak chronologies of living trees should be further extended into the past. Local structural, art-historical, and archaeological timber should be investigated in greater detail. There are some floating chronologies of historical oak from Latvia and Lithuania (Vitas and Zunde 2008) and a chronology of oak timber excavated from the Lower Castle of Vilnius dated to 1202–1418 (Pukienė and Ožalas 2007). Until now, the reconnaissance in the collections of the Estonian National Museum by Alar Läänelaid, Kristina Sohar and Ülle Jäe has revealed a lack of oak wood use in Estonian households. This valuable timber was mainly used in some pieces of furniture and in commodity and decorative details showing too short tree-ring series. There is also a paucity of oak in construction, as mainly pine and spruce were used in Estonian buildings (Läänelaid 2002). Some potential for extending the oak chronologies, or at least creating floating chronologies, can be achieved by studying trunks buried in sediments. According to geologist Alar Rosentau (pers. comm.), a trunk from Ruhnu Island has been radiocarbon dated as 3990–3720 cal BP.

3.3. Sapwood estimates in the eastern Baltic region

3.3.1. Sapwood statistics

The sapwood-heartwood boundary was determined using the colour criterion in 660 samples, and with the tyloses criterion in 630 cores, since 30 cores showed tyloses in the latest rings just beneath the bark, and these were not further used (Fig. 3a in Publication II). The two criteria overlapped in 63% of samples. The trees could be considered to be mature, since ca 80% belonged to the 100–200 year age class. Thus sapwood variance depending on age was not analysed here. As a result, the median sapwood ring count based on the colour and tyloses criteria in the three Baltic countries and Finland was 12 (Fig. 4 and Table 3 in Publication II). Within 95% confidence limits, sapwood number by colour varied from 6–19 rings. In more detail, 4–21 rings in the southern Finnish and western Estonian geobotanical group and 6–18 rings in the eastern Estonian, Latvian and Lithuanian group. However, the results based on the tyloses criterion showed a slightly wider range, giving a 95% range of 3–18 rings for the whole region, and 2–22 and 4–18 for two geobotanical groups, respectively.

Site median sapwood number slightly decreased eastward (Fig. 6 in Publication II). Although the model described only 21% of the total dispersion, this longitudinal gradient may be caused by the shift from a sub-Atlantic to a subcontinental climate. At the same time, the latitude-based model had even lower predictive value (12%), in other words, the length of daylight and the growing season were not essential in such a small area. Moreover, the dataset was spatially tilted southwards following the natural distribution of the oak population. As the historical Baltic timber has proved to originate from even further eastward areas, particularly from modern Belarus, Ukraine and Russia (e.g. Zunde 1998–1999), further investigations are necessary to explain more precisely the variability of the amount of sapwood in Eastern Europe.

Nevertheless, when comparing the results with the earlier studies (Table 1), the general eastward trend of the decreasing sapwood ring number of oaks in Europe was confirmed (Baillie et al. 1985; Hillam et al. 1987). The closest matches to the values presented here come from Finland and Poland. Thus sapwood values of 7–24 with a mean of 13.9 (Baillie et al. 1985) and of 8.32–21.80 within the 95% confidence interval (Briffa unpublished cit. Haneca et al. 2009) have been given for southwestern Finland. The main difference between this and the presented southern Finnish and western Estonian data (Table 3 in Publication II) lies in the minimal sapwood number, which also affects the mean. This may be due to site-specific causes as well as to different sample size. Annala and Tammisto, located in the greater Helsinki region, were represented by 20 cores, while Ruissalo and Solböle, located in the Archipelago Sea, were represented by 60 cores (Baillie et al. 1985). For Poland 9–24 rings (Ważny 1990) or 9–23 rings within 90% confidence limits (Ważny and Eckstein 1991) have been presented. The results introduced here (6–19 rings) show both lower values as well as a tighter range.

In addition to geographical variation, it is known that the quantity of sapwood also varies depending on the age and intensity of radial growth. It was noticeable that the slowly growing trees had slightly more sapwood rings than those with fast growth in the studied region, although the model had low predictive ability (Fig. 5 in Publication II). Nevertheless, a similar relationship has been reported before (e.g. Hughes et al. 1981; Wrobel and Eckstein 1993), but the model is more descriptive for younger oaks (Hillam et al. 1987). Sapwood most likely varies due to habitat type, water regime etc. But as the exact provenance of wooden material under the dating is usually unknown, these factors are irrelevant in estimating the missing sapwood.

3.3.2. Problems in detecting the heartwood-sapwood boundary

The primary problem in sapwood analysis is how to identify the boundary between the heartwood and the sapwood if the colour and the tyloses criterion mismatch. In cases of uncertainty, Hughes et al. (1981) have used the tyloses criterion rather than colour change. However, Savill et al. (1993) have determined the boundary as the first line of earlywood vessels at which tyloses were present in >75% of the vessels within the region of colour change in the wood. The sapwood and heartwood in different oak species can be differentiated by adding the chemical solution of methyl orange on a cross-section and observing the colour contrast (US Forest Products Laboratory 1954).

Here, the determination was made by the two criteria separately, as these did not coincide in 37% of samples. For instance, there were cores in which discolouration had started earlier than the formation of tyloses, and vice versa; cores in which the vessels in the latest rings had either partly or completely filled with tyloses (Fig. 3 in Publication II). The latter were excluded from the tyloses analysis. In addition, there were cores in which few filled rings were present in the middle of lighter sapwood and empty vessels. In such cases the boundary was marked by the latest ring with tyloses. That is why the records show so few sapwood rings according to the tyloses criterion in some cases (Fig. 4 and Table 3 in Publication II). It is known that these 'irregular' tyloses can also form in the sapwood after felling (Murmanis 1975). According to Zürcher et al. (1985 cit. Schweingruber 2007), besides the regular tyloses which obstruct vessel lumen for sap flow in the transition area between the heartwood and the sapwood, traumatic tyloses may occur, and these form after injuries or fungal attacks or soon after chopping of the tree. Moreover, it is known that tyloses rarely occur in the same ring around the whole stem. Here core samples from only one side of each trunk were used, and it is not known how the tyloses developed in the other sides.

Empirically it can be said that the traumatic tyloses prefer to form in moist core samples, while samples dried directly after coring exhibit this phenomena to a lesser degree. For instance, based on the Kuremaa data set (n = 12), the traumatic tyloses phenomena was observed. Sapwood volume was recoded and photographed directly after coring and rechecked each day during the following week. The samples were kept in plastic tubes without a cap at room temperature. The amount of sapwood began to change on the third day. By the seventh day, four samples had formed new tyloses under the bark. One example is shown in Fig. 7. Furthermore, the colour border was also blurred in some samples. Accordingly, both tyloses as well as colour criteria are somewhat subjective and only work out with a sufficient dataset. Nevertheless, the colour criterion was preferred in the conclusion.

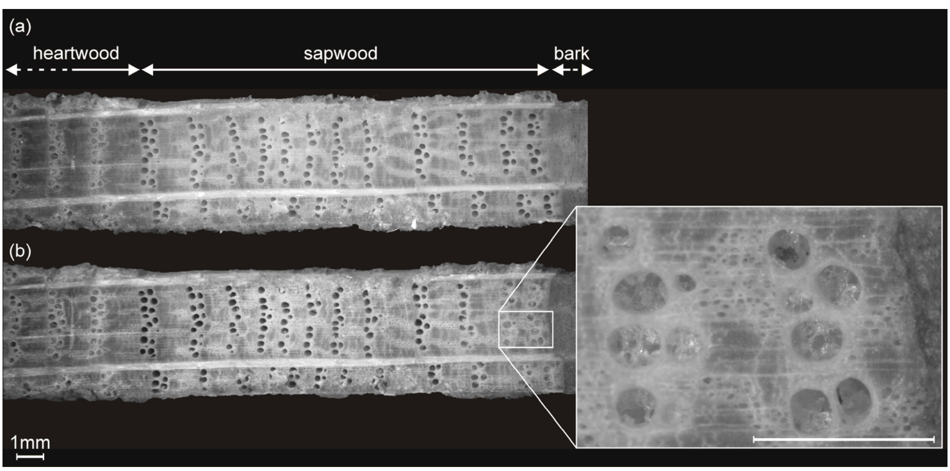

Figure 7. An oak sample immediately after coring (a) (07.11.2011) and seven days later (b) (14.11.2011), when traumatic tyloses have been formed in the vessels under the bark.

3.3.3. Use of sapwood estimates

An oak sapwood estimate of 6–19 rings for the eastern Baltic is presented above, based mainly upon trees 100–120 years old. This gives benchmarks for the evaluation of missing sapwood and thereby increases the dating precision for artefacts made of eastern Baltic oak. So far, sapwood estimates from Poland have been used to specify felling dates in the whole eastern Baltic region (e.g. Pukienė and Ožalas 2007). This is, of course, justified if the precise provenance of historical wood is unknown, since it most probably originates from the southern Baltic region and its eastward areas (i.e. from the catchments of the Vistula, the Neman, and the Daugava rivers) (e.g. Ważny 2005). Thus the used sapwood estimates should be derived from the respective reference chronology.

The first practical use of eastern Baltic sapwood estimates was in dating a Neo-Renaissance cabinet from the collection of Suuremõisa castle in Estonia that had been restored by Riiel (2012). Seven of the studied boards out of the total of nine contained some sapwood, maximally 12 rings. The measured tree-ring series cross-dated most closely with the Lithuanian and the western Belarusian oak chronology (Bitvinskas and Kairaitis 1975). Applying the range of 6–19 sapwood rings, the felling date of the trees may lay between the years 1905 and 1910.

During the application of the presented sapwood estimates, one must keep in mind that these have been derived from the cores of living trees at breast height. Sapwood increases as one moves up the trunk, changes within cross-section, and enlarges with the ageing of a tree (e.g. Hughes et al. 1981; Hillam et al. 1987). This must be considered when dating historical timber. Historically, timber was seasoned and stockpiled as well as re-used. Objects were often repaired. All of this should be taken into account (e.g. Miles 2006).

3.4. Climatic signals in the Estonian and Finnish chronologies

The northern distribution of oak is considered to be limited by cold winter, frost and short growing season (e.g. Repo et al. 2008). Causes of oak's existence were not, however, studied here. Factors that influence the radial growth, i.e. tree-ring width, were investigated instead.

3.4.1. Summer

The results of the correlation and response analyses on the regional level in Estonia are demonstrated in Fig. 6 in Publication IV, and the strongest relationships are shown in Fig. 8. It revealed that the western oak chronology was significantly positively correlated to June, July, and August precipitation, with a positive response coefficient to June rainfall only. By contrast, the northeastern chronology showed a significant positive correlation to June temperature only. All of these relationships were especially pronounced during the pointer years. Moreover, summer precipitation and June temperature in the negative pointer years were significantly lower than during the ordinary years in the western and northeastern regions, respectively. In the southeastern sites both July precipitation and July temperature were the significant factors to growth. On the countrywide scale, the relationships are weaker (not shown), which can be attributed to a greater variation in both the weather and tree-ring series. In the studied southern Finnish site, oak growth especially benefitted from June and July rainfall, and a bit less by spring temperature (Fig. 8; Table 3 and Fig. 5 in Publication III).

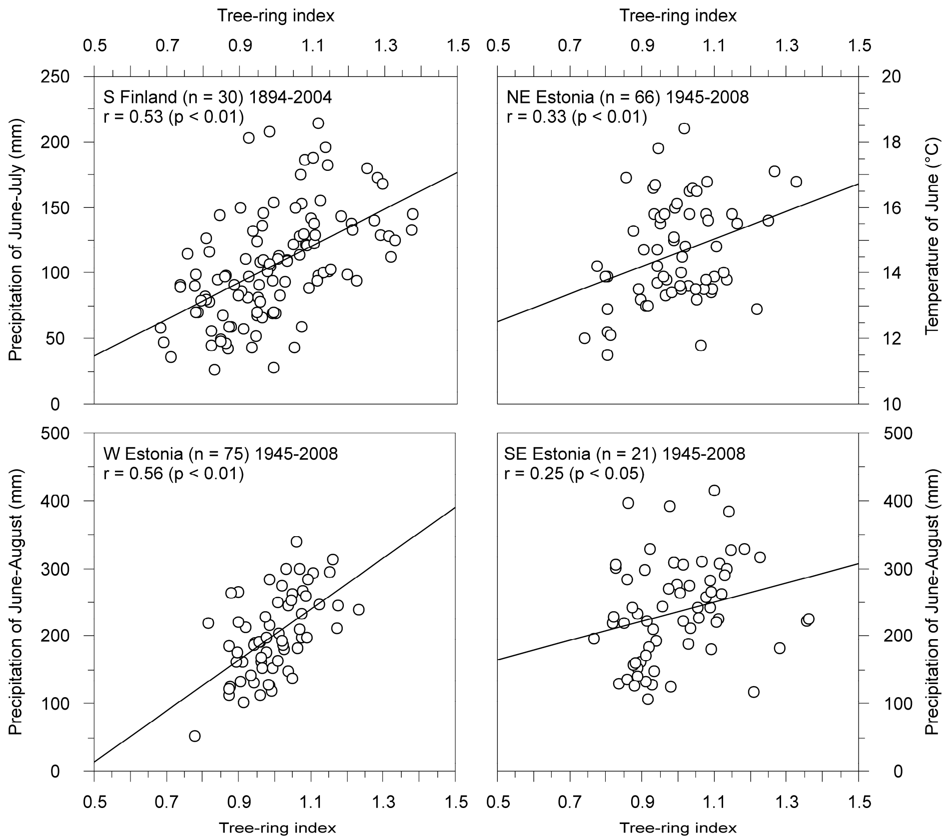

Figure 8. The strongest relationships between the tree-ring indices and the weather variables in the studied regions shown as scatter plots with Pearson's correlation coefficients (r). Sample size in the chronology (n) is shown in brackets.

As the western Estonian sites are located on shallow soils on carbonate rock (rendzic soils), dry summers likely cause water stress. The same is true in the southern Finnish site, where the shallowest soil observations around the trees on the sporadically exposed bedrock ranged between 8 and 76 cm (Publication III). The importance of summer precipitation for oak growth has long been known (Stewart 1913), and has been described widely throughout Europe (e.g. Pilcher and Gray 1982; Santini et al. 1994; Tessier et al. 1994; Bridge et al. 1996; Rozas 2001, 2005; Lebourgeois et al. 2004; Čufar et al. 2008a, 2008b; Friedrichs et al. 2009), and in closer regions in Finland (Hilasvuori and Berninger 2010), in Sweden (Drobyshev et al. 2008), and in Poland (Cedro

2007; Bronisz et al. 2012). Consequently the oak decline observed in the southern Finnish site was attributed to the inhibiting effect of sequential summer droughts (Publication III). This conclusion is supported by a previous oak decline study from Finland, which showed drought-incited oak mortality on the shallow soil (Helama et al. 2009). Drought-induced or at least drought-influenced dieback has been shown by several authors (e.g. Siwecki and Ufnalski 1998; Drobyshev et al. 2007; Allen et al. 2010; Andersson et al. 2011).

In contrast, the significant lack of precipitation effect in the northeastern Estonian sites can be attributed to the deeper and drought-resistant cambic soils and Luvisols, where the roots are more steadily provided with water. Oak growth in subcontinental western Latvia depends positively on spring and summer temperatures (Matisons et al. 2013). This corresponds to our results from similar soils in northeastern and southeastern Estonia. However, the oaks in continental eastern Latvia prefer milder winters and suffer from excess soil water. In Lithuania a positive correlation between summer temperature and tree-ring width occurs only in the temporarily inundated sites, as oaks growing in well-drained sites prefer a moist, warm summer (Ruseckas 2006). Alternatively, other studies from the eastern Baltic region have shown a negative effect of summer temperature (Ważny and Eckstein 1991; Cedro 2007; Drobyshev et al. 2008). In the southeastern region, the impact of weather is not as pronounced as in the other regions, but both a moist and a warm growing season appear to be favourable. As these sites lie on more drought-prone sandy soils, a positive effect of soil moisture makes sense. In conclusion, high summer temperatures do not limit oak growth in continental Estonia, i.e. temperature does not exceed the optimum there.

Similarly to oak growth, spruces in Estonia are mostly enhanced by summer (June) rainfall (Läänelaid and Eckstein 2012). However, the chronologies themselves do not match, as shown above. The reasons for this can be physiological instead.

3.4.2. Winter and spring

Annual ring width showed no significant relationship to temperature during the deep dormancy period in Finland and in Estonia (Fig. 5 and Table 3 in Publication III; Fig. 6 in Publication IV), except in the specific Loode site on Saaremaa Island (Fig. 4 in Publication I). The latter can be explained through the appearance of permanent snow-cover during below-zero temperatures, and thus better root insulation, which has also been suggested as a possible reason by Helama et al. (2009).

However, the influence of dormancy and spring conditions emerged on a more detailed scale, i.e. in early- and latewood (Table 3 and Fig. 5 in Publication III). It appeared that earlywood width was especially controlled by winter (December–February) and spring (March–May) temperatures, which means that mild rather than cool winters and warm springs are more favourable to earlywood formation in the Tammisto in Finland. As earlywood involves the water-conducting vessels, the timing of ground melting and ground water accessibility becomes relevant. Earlywood growth in the White Carpathians in the Czech Republic has been associated with the previous autumn and winter temperatures (Doležal et al. 2010). In Latvia, vessel lumen area, another earlywood characteristic, also shows the highest positive correlations with winter and spring temperatures (Matisons and Brūmelis 2012).

Even if oak earlywood vessels enlarge in a short time in spring, between the bud break and leaf expansion (Sass-Klaassen et al. 2011), the process can depend on the previous year's latewood (Nola 1996). Moreover, earlywood vessel elements in ring-porous hardwood most probably originate from overwintered cambial derivatives (Kitin et al. 1999). A higher correlation between the current year's earlywood and the preceding year's latewood width than the same year's corresponding portions has been demonstrated by Nola (1996), García González and Eckstein (2003). This was also confirmed by the Finnish data (Table 2 in Publication III).

On the other hand, latewood was enhanced by summer (especially June–July) rainfall, as was the whole annual ring in the Tammisto in Finland. This can be explained by the fact that annual ring width varies more with latewood than with earlywood width, which was more constant over time (Fig. 9; Table 2 in Publication III). That has also been demonstrated by other authors (e.g. Lebourgeois et al. 2004; Doležal et al. 2010; Matisons and Brūmelis 2012).

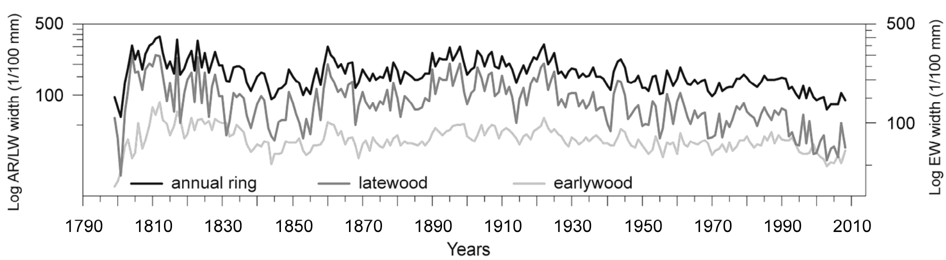

Figure 9. The Tammisto average oak chronologies (n = 30): the annual ring (black line), the latewood (dark grey line) and the earlywood (light grey line).

Correlations between the annual ring indices with April, May, and June monthly minimum temperatures showed no statistically significant positive relationships on the regional level in Estonia (Publication IV). On the site level, only the Mäetaguse oaks in northeastern Estonia seemed to suffer from late frosts in June ($\rho = 0.32$; $p < 0.05$). Thus occasional frosts at the beginning of the vegetation periods do not affect tree-ring development during the ongoing growing season. Alternatively, occasional chills may have been absent in the monthly minimum temperature record, or their appearance depends more on site microrelief.

In addition to temperature and precipitation, tree-ring width may be correlated with large-scale atmospheric circulation using, for example, the

Southern Oscillation index (e.g. Rozas and García González 2012b) or the North Atlantic Oscillation index (e.g. Roig et al. 2009). The latter describes the intensity of the westerlies and is correlated to air temperature, precipitation, snow cover and sea ice in Northern and Central Europe during the winter (Hurrell 1995; Hurrell and van Loon 1997; Jaagus 2006a, 2006b). Here it was shown that oak growth was weakly correlated to the NAO indices in Estonia (Fig. 7 in Publication IV). Only in the northeastern region the relationship between the March NAO index and radial growth was continuously significant during most of the observed period. This generally means that wider tree rings occur in years with a positive NAO phase, which describes intense westerlies with mild, snowless winters. In such years spring starts earlier and probably the vegetation period is longer, and hence wider tree rings can form. Contrarily, the Estonian pine chronology correlates closely with the winter (December–March) NAO indices (Läänelaid et al. 2012). This makes sense, since winter and early spring temperature is established as the climatic signal contained in the Estonian pine chronology (Läänelaid and Eckstein 2003).

3.4.3. Pointer years

The identified pointer years in the Estonian oak chronologies (Table 1 in Publication IV) reflected regional weather extremes. Accordingly, the narrow tree rings coincided with dry summers in the western region and with cool summers in the northeastern part of the country.

However, comparing these pointer years with the pan-European oak signature years (Kelly et al. 2002), one must admit that there is a poor correspondence. Some correspondence with the negative pointer years was detected in 1909, 1923, 1928, 1940, and with the positive pointer years in 1910, 1924, and 1978. Moreover, there were even years that showed a contrary course to the pan-European data sets (1950, 1956, 1962, and 1979). The reasons behind the disagreements may be the higher sample size and the westward-tilted geographical distribution of the Europe-wide data set.

Nevertheless, more similarities become evident in the context of the adjacent Latvian pointer years (Matisons et al. 2013). For instance, common negative pointer years appeared in 1909, 1914, 1928, 1932, 1940, 1947, 1955, 1977, 1986, 1993, 2004, and common positive pointer years in 1919, 1922, 1938, 1957, 1978, 1980, 2001, 2007, either on the countrywide or a regional scale. Also, common negative pointer years with the Swedish oaks fell in 1868, 1940, and 1947 (Drobyshev et al. 2008).

Thus the Estonian pointer years mostly reflect the local weather variations of the region.

3.5. Precipitation reconstruction

Based on the principle of uniformitarianism, it can be assumed that the processes occurring today are the same as those that occurred in the past (e.g. Speer 2010). This basic assumption enables us to reconstruct the past climate. Thus it is assumed that the factors that influence tree growth have all been the same in the past as in the present.

Accordingly, since June–August rainfall correlated most accurately with the western Estonian chronology, the corresponding tree-ring width data can be used as a proxy for reconstructing summer precipitation back to the year 1769 in the region (Publication IV). The created model explained 21% of the variance in the instrumentally observed rainfall series (Fig. 8 and Fig. 9 in Publication IV). One can consider this to be modest predictive skill, although other oak tree-ring based retrodictions of European hydroclimates have shown just slightly better results. For example, models with 32–35% predictive skill for the spring–summer precipitation in southern England (Cooper et al. 2013; Wilson et al. 2013) and 37–38% for annual precipitation in western Hungary (Kern et al. 2009) have been produced. Drought index reconstructions have explained ca 30% and 44% of the instrumentally observed variance in southern Sweden (Drobyshev et al. 2011) and 20–47% in southeastern Slovenia (Čufar et al. 2008a). Overall, there are more tree-ring based reconstructions of temperature than precipitation for temperate Europe, and most of these are conifer-based (e.g. Hughes et al. 1984; Briffa et al. 1988a, 1988b, 1992; Eronen et al. 2002; Gunnarson and Linderholm 2002; Helama et al. 2002; Büntgen et al. 2013).

Further on, the reconstruction validation did not show a significant relationship with the instrumentally recorded summer precipitation over the whole of Estonia (1866–1919; Fig. 9 in Publication IV). This may be related with the great spatial variability of precipitation (Jaagus 1999). Also, the earlier instrumental records mainly originate from Tartu (southeastern Estonia), which is poorly representative of western Estonia. The anomalies in the reconstruction of the pre-instrumental period were validated against historical information from chronicles as compiled by Vahtre (1970), and this proved to be somewhat satisfactory. Accordingly, the strong and extreme negative peaks in the reconstructed series were associated with cases of water deficit and severe droughts (4 out of 9), while the strong and extreme positive years could be mainly associated with chilly and moist conditions (9 cases out of 13) (Fig. 9 in Publication IV).

The relatively low predictive skill can be accounted for the fact that the limiting factor may change among the years and even at one time, radial growth is limited by multiple factors. The growth period determined by rainfall may vary from year to year and the impact may be more detailed in time. Thus weekly instead of monthly data is needed to further explain weather influence on oak growth. Also, the conditions during the previous growing season should be included to the model. Nevertheless, the reconstruction model has adequate capacity of detecting past rainfall extremes.

4. CONCLUSIONS

This thesis provides an overview of the dendrochronological and dendroclimatic potential of pedunculate oak at its northern distributional limit in Finland and the Baltic States, with a specific focus on oaks growing in Estonia. The main conclusions are as follows.

1) The first countrywide oak chronology was constructed for Estonia covering the period 1646–2011. The radial growth pattern of oak is quite similar across the country, reflecting a common trans-regional summer precipitation variance. On a detailed scale, at least three spatial groups – the western, northeastern and southeastern – can be distinguished. In order to strengthen the chronology, the sample size from the southern region should be extended in the future. Moreover, the created chronology based on living trees is a good basis to extend it back into the past with historical timber hereafter.
2) The Estonian oak chronology showed an evenly strong teleconnection with the Finnish, Latvian and Lithuanian oak chronologies. Northern Poland can be considered to be the southern limit of the region in which some similarity with Estonian oaks can be established. However, heteroconnection between oak and conifers is low in Estonia. There is a prospect for studying oak teleconnection on the westward-eastward gradient, and to investigate heteroconnection with other deciduous species (e.g. ash) in the future.
3) Sapwood number within 95% confidence limits ranges from 4–21, 6–18, and 6–19 in southern Finland and western Estonia, in eastern Estonia, Latvia and Lithuania, and in the eastern Baltic region combined, respectively. These estimates should increase the precision of oak dating in the region. Regarding earlier studies, the general European trend of decreasing sapwood ring number towards the east was confirmed. A spatial pattern of eastward decrease in median sapwood ring number was also noticed within the studied region.
4) At the northern distributional limit, oak's radial growth is limited by the summer weather. In general, the larger the area, the weaker the relationship with the weather. Due to site distance from the sea and the soil, the increment is controlled by summer precipitation during June–July in Finland and during June–August in western Estonia, by June temperature in northeastern Estonia, and both summer temperature as well as rainfall in southeastern Estonia. Moreover, sequential summer droughts are considered to be one of the potential predisposing factors of oak decline in the studied Finnish forest. On the seasonal level, latewood and the total annual ring width show similar responses, while earlywood, which determines the total annual increment to a lesser degree, is more enhanced by the warmer winter and spring in Finland.

5) The first tree-ring based palaeoclimatic reconstruction for Estonia was presented. However, the oak growth pattern can be considered a poor climate proxy, as the constructed model explained only 21% of the variance in actual summer rainfall in western Estonia. This suggests that extreme weather events described in the historical sources may be local in their character, and precipitation in general has great spatial variance. Nevertheless, the reconstruction model can retrodict years of extreme summer precipitation in the region.

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SUMMARY IN ESTONIAN

Soome ja Baltimaade tammede dendrokronoloogia ja seosed ilmastikuga

Globaalne kliimamuutus on tänapäeva üks põletavamaid teemasid. Võimalike arengute prognoosimiseks on vaja mõista mineviku kliimat. Üks võimalus selleks on uurida puude aastarõngastes talletunud mineviku sündmusi ja keskkonnatingimusi. Aastarõngaste ja ilmastiku seoste analüüsimisega ning nende järgi mineviku kliima rekonstrueerimisega tegeleb dendroklimatoloogia. Eestis ja selle naaberriikides on uuritud okaspuude dendrokronoloogilisi ja -klimatoloogilisi aspekte ning rakendatud neid aastarõngasdateerimisel, kuid hariliku tamme (*Quercus robur* L.) aastarõngalaiuste ajalist varieeruvust ning nende seoseid ilmastikuga on siin seni vähe analüüsitud.

Käesoleva väitekirja eesmärgiks oli uurida hariliku tamme dendrokronoloogilist ja -klimatoloogilist potentsiaali liigi levila põhjapiiril Soomes ja Baltimaades, põhjalikumalt Eestis. Täpsemad ülesanded olid järgnevad:

1) koostada Eestis kasvava tamme aastarõngalaiuste kronoloogiad;
2) hinnata Eesti tammekronoloogia sarnasust naaberriikide vastavate kronoloogiatega ning Eesti okaspuude kronoloogiatega;
3) kirjeldada ja standardiseerida Soomes ja Baltikumis kasvava tamme maltspuidu aastarõngaste arvu varieeruvus;
4) tuvastada Soomes ja Eestis kasvava tamme radiaaljuurdekasvu mõjutavad ilmastikutegurid;
5) hinnata Eestis kasvava tamme aastarõngalaiuste kasutamise võimalikkust paleoklimaatiliseks rekonstruktsiooniks.

Selleks analüüsiti 740 tamme puursüdamikku 47 proovialalt. Neist 192 proovi andmeid Soomest ja Eestist kasutati dendroklimatoloogilisteks analüüsideks ja 668 proovi andmeid Soomest ja Baltimaadest maltspuidu määramiseks. Puursüdamikelt mõõdeti mikroskoobi all aastarõngaste laiused, Soome proovidel eraldi ka vara- ja hilispuidu laiused. Lisaks loendati maltspuidu aastarõngaste arv. Standardiseerimisega eemaldati mõõdetud aastarõngalaiuste ridadest paljuaastased madalsageduslikud võnked ning koostati üksteisega võrreldavad aastarõngalaiuste kronoloogiad. Kronoloogiaid võrreldi dendrokronoloogias kasutatavate statistiliste sarnasusnäitajate abil. Aastarõngalaiuste ridu korreleeriti erinevate ilmastikukarakteristikutega: kuude keskmine temperatuur ja sademetesumma, aprilli, mai ja juuni miinimumtemperatuur, kuude Põhja-Atlandi Ostsillatsiooni (NAO) indeksid. Lisaks leiti aastarõngalaiuste aegridadest näitaastad, mil tammedel esines erakordselt madal või kõrge juurdekasv. Juurdekasvuga kõige tugevamalt seotud ilmastikunäitaja põhjal, rekonstrueeriti paleokliimat.

Aastarõngalaiuste ridade alusel koostati eri piirkondade kronoloogiad. Selgus, et tammede juurdekasv on Eesti piirkondade vahel sarnane ning suuresti mõjutatud üle-eestilisest suvisest sademetemustrist. Sellest lähtudes koostati esimene üleriigiline 366 aasta pikkune tammekronoloogia (ajaline ulatus 1646–2011). Kuna kronoloogia on koostatud vaid kasvavatest tammedest, siis edaspidi on vajalik seda pikendada kaugemale minevikku. Selleks tuleb jätkata tammepuidust esemete ja arheoloogilise puidumaterjali uurimist. Eestis kasvava tamme juurdekasvumuster on sarnane Lõuna-Soome, Läti ja Leedu tammekronoloogiatega. Teatav sarnasus on ka Pommerimaa (Põhja-Poola) tammedega. Seega järeldati, et uuritud tammed kuuluvad ühte ja samasse dendroklimaatilisse piirkonda. Edaspidi tuleks uurida tammede juurdekasvumustri sarnasust lääne-ida sihil. Samas ei sarnane Eestis kasvava tamme juurdekasv kuigivõrd siinsete okaspuude juurdekasvuga. Seega, naaberalade tammekronoloogiaid saab dendrokronoloogilises dateerimises teatud üldistuses üksteisega asendada, kuid erinevate puuliikide kronoloogiatega mitte.

Maltspuit on tammepuidust esemetel ja ehituspuidus sageli eemaldatud, arheoloogilises puidus kõdunenud. Samas maltspuidus kui puu koorealuses puiduosas asuvad noorimad aastarõngad, mis on olulised tammepuidust esemete dendrokronoloogiliseks dateerimiseks. Puuduva maltspuidu aastarõngaste arvu tuvastamiseks uuritakse kasvavaid tammesid. Käesoleva töö tulemusena saab öelda, et Soome ja Lääne-Eesti tammede maltspuidu aastarõngaste arv varieerub 95% tõenäosusega vahemikus 4–21 aastarõngast, Ida-Eesti, Läti ja Leedu tammedel 6–18 ning kogu piirkonnas vastavalt 6–19 rõngast. Võrreldes neid tulemusi ülejäänud Euroopa sarnaste uuringutega leiab kinnitust fakt, et tammede maltspuidu aastarõngaste arv väheneb läänest itta. Soome ja Baltimaade sisene maltspuidu varieeruvus on väike, kuid maltspuidu hulk väheneb samuti ida suunas. Esitatud maltspuidu aastarõngaste arvu varieeruvuspiiride hinnang võimaldab tõsta Läänemere idakalda tammepuidust arhitektuuri- ja kunstiobjektide dendrokronoloogiliste vanusemäärangute täpsust.

Nii Lõuna-Soome kui ka Lääne-Eesti tammede juurdekasvumuster sõltub eelkõige suvistest sademetest. Seega, mida sademeterohkem on suvi, seda laiemad aastarõngad moodustuvad ning vastupidi, mida kuivem kasvuperiood, seda kitsamaks jäävad kasvukihid. Kirde-Eestis seevastu mõjutab puude juurdekasvu positiivselt suvine temperatuur ning Kagu-Eestis on nii temperatuuri kui sademetega positiivne seos. Selline ruumiline erinevus on seletatav sademete territoriaalse jaotusega Eestis ning proovikohtade erineva mullatüübiga. Kevadel ja suvel on merelise kliimaga Lääne-Eesti sademetevaesem kui mandrilise kliimaga Ida-Eesti. Lääne-Eesti tammikud aga kasvavad peamiselt põuakartlikel paepealsetel ja rähkmuldadel ning kuivemad suved pidurdavad seal puude radiaaljuurdekasvu eriti. Samas, Kirde-Eesti proovialadel on mullad tüsedamad ja põuakindlamad ning veepuudus pole pärssiv, küll aga pääseb mõjule suve alguse temperatuur. Juurdekasvu ja ilmastikutegurite vahelised seosed on tugevad just ekstreemsetel näitaastatel. Kagu-Eesti proovialad on seni veel alaesindatud ning proovialade hulga suurendamine edaspidi võimaldaks täpsemalt hinnata ilmastiku mõju. Ka Lõuna-Soome uuritud puistus kasvavad tammed väga õhukesel, kohati aluskorraga paljanduval mullal. Sealsete puude hääbumise üheks põhjuseks võib pidada viimastel aastakümnetel sagenenud põudasid. Seega on tamme radiaaljuurdekasv mõjutatud eelkõige suvekuude ilmastikust. Kui aga vaadelda aastarõnga erinevaid osasid – vara- ja hilispuitu – siis selgub, et kevadise varapuidu laius sõltub eelneva aasta hilispuidu laiusest ning talve ja kevade õhutemperatuurist, samas kui hilispuidu laius sõltub kasvuperioodi suvekuude sademetest. Ühtlasi määrab just hilispuidu hulk ära kogu aastase kasvukihi ulatuse. Varakevadiste öökülmade olulist mõju aastasele juurdekasvule ei tuvastatud. Samuti ei saadud ühtset seost NAO indeksi ja tamme juurdekasvu vahel. Viimase puudumine on seletatav eelpool mainitud suviste tingimuste olulisusega juurdekasvule, samas kui NAO indeks näitab läänevoolu intensiivsust talvisel poolaastal.

Töös esitatud Lääne-Eesti sademete rekonstruktsioon on esimene puude juurdekasvu põhjal koostatud Eesti mineviku kliima mudel. Tamme aastarõngalaiused kirjeldavad 21% sademete varieeruvusest. Saadud tulemust võib pidada tagasihoidlikuks, kuna Euroopas on varasemalt tamme aastarõngalaiuste põhjal kirjeldatud kuni ligi 50% sademete varieeruvusest. Samas, ajalooallikates toodud äärmuslike ilmastikuoludega kattuvad siin arvutatud ekstreemumaastad rahuldavalt. Seega on mudel võimeline tuvastama mineviku ekstreemseid põua- ja vihma-aastaid.

Kokkuvõtvalt, väitekiri selgitab tammede juurdekasvu mõjutegureid liigi levila põhjapiiril, tuvastab aastarõngaste põhjal äärmuslike sademetega aastaid ning parandab tammepuidu dateerimise täpsust.

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3. **Ülo Suursaar.** Soome lahe avaosa ja Eesti rannikumere vee kvaliteedi analüüs. Tartu, 1993.
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5. **Kjell Weppling.** On the assessment of feasible liming strategies for acid sulphate waters in Finland. Tartu, 1997.
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8. **Valdo Kuusemets.** Nitrogen and phosphorus transformation in riparian buffer zones of agricultural landscapes in Estonia. Tartu, 1999.
9. **Kalev Sepp.** The methodology and applications of agricultural landscape monitoring in Estonia. Tartu, 1999.
10. **Rein Ahas.** Spatial and temporal variability of phenological phases in Estonia. Tartu, 1999.
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