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DEVELOPING MILLENNIAL TREE-RING CHRONOLOGY FOR TURKU (ÅBO) AND COMPARING PALAEOCLIMATIC SIGNALS INFERRED FROM ARCHAEOLOGICAL, SUBFOSSIL AND LIVING *PINUS SYLVESTRIS* DATA IN SOUTHWEST FINLAND

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Abstract:
Archaeological and living tree data were used to construct tree-ring chronologies over the medieval (AD 1183–1430) and recent (AD 1812–2020) periods in Turku, which is historically an important population centre in Southwest Finland and the country. Comparisons between the two tree-ring assemblages, and between the previously built chronologies from the Åland (historical timber) and Tavastia (lacustrine subfossils and living trees) sites, provided ways of understanding the growth patterns and their linkages to climatic, environmental, and edaphic factors. Tree growth in and around Turku was affected by warm-season precipitation and winter temperature. Similar relationships were previously evident also in the Åland tree rings, whereas the data from a wetter Tavastia site did not exhibit similar precipitation signal. The site conditions influence also the correlations which are higher between Turku and Åland than between Turku and Tavastia chronologies. Construction of long continuous chronology is impaired by human-related activities, the Great Fire of Turku in 1827 and logging, which have diminished the availability of dead and living-tree materials, respectively. These conditions lead to hardships of filling the gap between the medieval and recent periods and updating the archaeological datasets with compatible living-tree data, which are both demonstrated by our results.

Key words: dendrochronology, archaeology, vegetation history, construction timber, subfossil wood.

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INTRODUCTION

Long tree-ring records are needed for dating of historical and archaeological materials and for interpretations of past climate variability. Tree growth patterns reflect climatic and environmental changes with annual precision and accuracy (Fritts, 1976; Baillie, 1995). Compared to other methods available to date wood materials, based on ^{14}C (Hajdas *et al.*, 2021; Pearson *et al.*, 2022) or molecular decay (Tintner *et al.*, 2020), tree-ring dates come with annual resolution and without uncertainties. The dating issue also concerns the special case of ^{14}C dating by wiggle matching (Wacker *et al.*, 2014; Kuitems *et al.*, 2022), which actually requires precise high-resolution materials such as tree rings to work ideally. In fact, the recent developments in ^{14}C dating methods emphasise the growing need of dendrochronologically analysed sample materials.

Here we explore tree-ring data from wooden materials originating from urban archaeological excavations carried out in Turku (Åbo), Southwest Finland. Moreover, the archaeological tree-ring collections are analysed with data collected from living *Pinus sylvestris* trees growing in the same region. There are several reasons to focus on these data. First, the archaeological excavations have uncovered

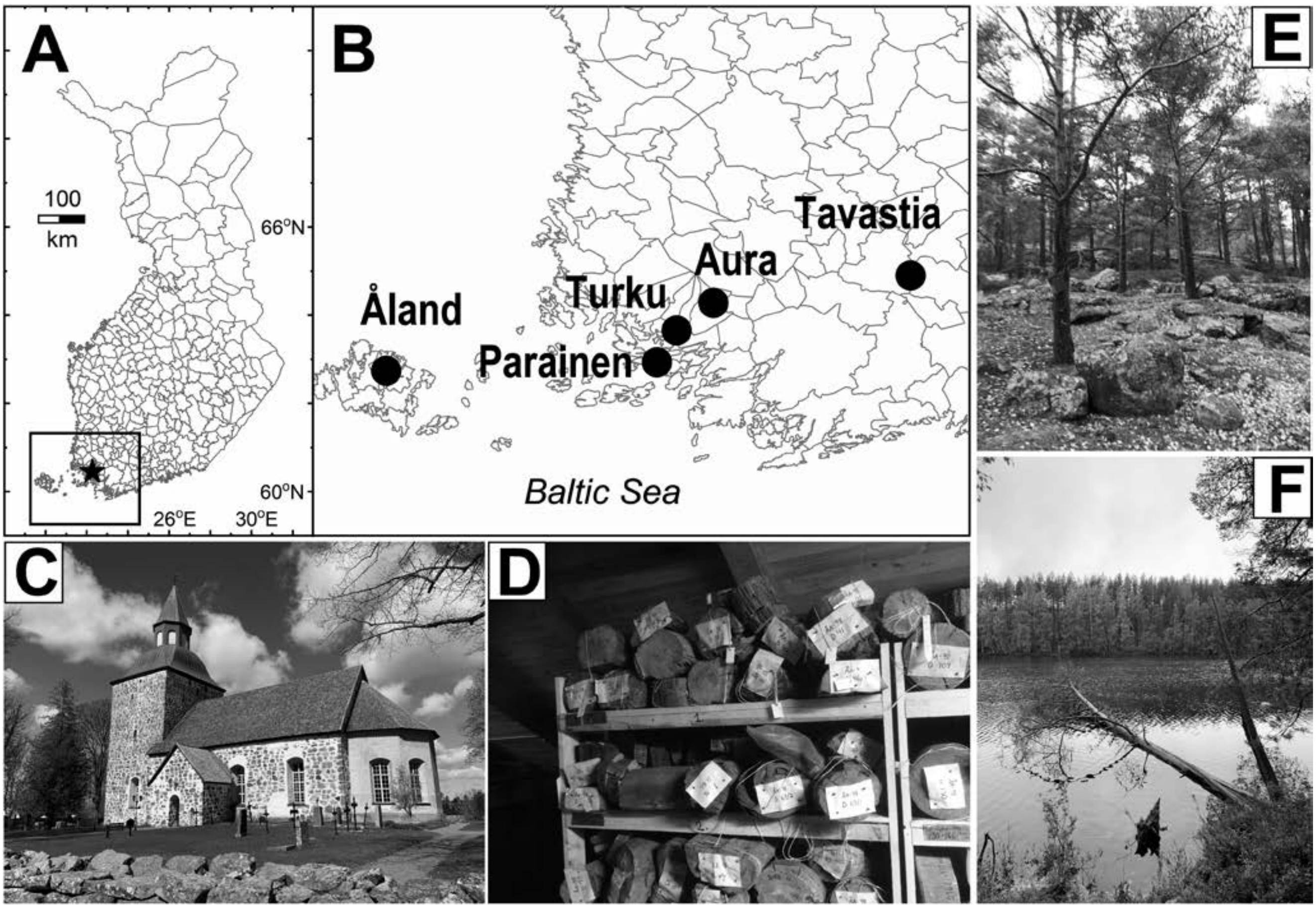

Fig. 1. Map of Finland, with the study region indicated by a rectangle, and location of the City of Turku indicated by a star (A). The inlet (B) indicates locations of the Turku, Åland and Tavastia chronologies, and the sites of two additional chronologies (Parainen and Aura) as components of the regional tree-ring chronology sites near Turku in Southwest Finland. Tree-ring materials for the Åland chronology originate from stone churches (C), for the Turku chronology from the Museum Centre of Turku (D), the living trees chronologies represent the Parainen, Turku and Aura sites (E), and the Tavastia chronology the wet riparian zone adjacent to the lake with subfossil pinewood stems forming the subfossil part of the chronology (F).

a large number of wooden objects such as construction timber representing pinewood materials (Zetterberg, 2003; Seppänen, 2012). Second, tree-ring data representing the living trees have been previously analysed for their statistics and climatic signals over the 1960–2019 period (Helama, 2022). In this study, these data are presented as modern updates for the archaeological data. Combined, the two types of data can now be analysed as a composite tree-ring chronology. In addition, dendroclimatic comparisons with temperature and precipitation records are extended in this study over the 1910–2019 period, for an improved understanding of climatic signals. Third, it is also noteworthy that one of the earliest dendrochronological/dendroclimatic investigations in Europe was carried out in Turku, conducted by Johan Leche during the 1750s (Norrgård and Helama, 2021). Since then, there have not been intensive tree-ring studies focusing on trees of Turku or the forests surrounding the city.

Collectively, the aim of this study was to develop a new millennial tree-ring chronology representing climatic variability from medieval times to present-day, for sites with deep occupation and scientific history in Southwest Finland, while also discussing the hardships of updating archaeological tree-ring datasets with more recent data.

MATERIAL AND METHODS

Archaeological tree-ring samples

A collection of archaeological pinewood (*Pinus sylvestris* L.) samples was analysed for their use in dendrochronology. This set of sample disks (n = 247) originates from the archives maintained by the Museum Centre of Turku. The specimens were previously unearthed during the archaeological excavations conducted in Turku in Southwest Finland/Finland Proper, between 1988 and 2011 (Fig. 1). Ring widths were measured on the cross-section of the disks to the nearest 0.01 mm under the light microscope. For each cross-section, two radii were typically measured to produce ring-width series from pith to the outermost available ring. However, the shape and/or physical condition of some of the sample disks (n = 41) did not allow more than one measured radius. Moreover, some of the samples were too decayed to be dendrochronologically inspected. Finally, the number of samples with tree-ring measurements totalled 234.

Tree-ring dating

Dendrochronological cross-dating was performed both visually and statistically. First, multiple radii from each sample were compared to identify potentially missing or falsely added rings in the series. Second, the sample series were correlated against the existing master chronologies from the Tavastia Proper region (Helama *et al.*, 2014) and the Åland Islands (Helama and Bartholin, 2019) (Fig. 1). Both these chronologies represent *P. sylvestris* ring widths. The Tavastia chronology covers the 1147–2000 period and is built from subfossil tree-ring samples unearthed from the sedimentary deposits of Lake Kaitajärvi and Lake Vähä-Melkutin, in combination with samples from living trees growing near the lakes (Helama *et al.*, 2014). The Åland chronology originates from the archipelago (ca 60°N, 20°E) between the mainlands of Finland and Sweden. This chronology is built from historical samples collected from the stone churches and their architectural structures (Ringbom *et al.*, 1996) and spans interval between the years 1057 and 1826 (Helama and Bartholin, 2019). Distance from Turku to Åland site is ca 125 km and that between Turku and Lake Kaitajärvi/Lake Vähä-Melkutin sites ca 100 km.

Tree-ring widths were standardized by transforming the raw data into dimensionless indices by fitting a 32-year spline function (Cook and Peters, 1981; Cook *et al.*, 1990a) to the series and dividing the observed values of ring widths by the values of the curve. Spline function with similar rigidity (i.e., 32-years) has been generally recommended for standardizing tree-ring series prior to cross-dating (Grissino-Mayer, 2001). Moreover, the series were pre-whitened to remove the remaining autocorrelation (Cook *et al.*, 1990b). Pre-whitening of the series prior to cross-dating is frequently recommended (Cook, 1985; Monserud and Yamaguchi, 1989; Grissino-Mayer *et al.*, 2010). The Tavastia and Åland master chronologies were produced by averaging the standardized tree-ring series into the respective mean chronologies. The sample series from the Museum Centre of Turku, standardized in similar fashion, were cross-dated against these existing tree-ring chronologies.

In the dating process, in which a single sample series was correlated with the master chronologies, each sample was lagged forward and backward in time to determine whether offsetting the time series would yield a high (positive) correlation coefficient. The Pearson product-moment correlation coefficients (r), which is commonly used in tree-ring dating (Holmes, 1983), were calculated. In this study, the chronological positions with highest (r_1) and second highest (r_2) correlation coefficients were determined for each sample series (Helama, 2023). Comparison between r_1 and r_2 was quantified using the z-statistic (Pearson and Filon, 1898; Diedenhofen and Musch, 2015). Previously, it was shown that the 5% level of statistical significance (i.e., $p < 0.05$) for r_1 minus r_2 could be obtained with $z > 0.6$ for a millennial *Pinus sylvestris* ring-width chronology from southeast Finland (Helama, 2023). Similarly, the $z > 0.6$ criterion was adopted here as an indication for statistically significant assessment of r_1 minus r_2-statistic.

First, cross-dating of each sample series was carried out separately for the Tavastia (Helama *et al.*, 2014) and Åland chronologies (Helama and Bartholin, 2019), and for their mean record. When the dating results of a single series/sample with the master chronologies did not agree, the dating of the sample series was disregarded. Second, a new master chronology for Turku was created by averaging the series that cross-dated against the existing master chronologies. Third, the series that remained undated were re-examined by cross-dating them against the master chronology of Turku, the mean chronologies of Turku and Åland, Turku and Tavastia, and Turku, Åland and Tavastia. An increased number of sample series now dating against these chronologies were added to the Turku master chronology. This procedure was repeated two more rounds.

Living-tree samples and data

To update the Turku chronology with recent materials, a set of living *P. sylvestris* trees were sampled in a forested site in the City of Turku (60°28’N 22°15’E). The fieldwork was carried out in October 2019. To expand the spatial coverage of the living-tree dataset, additional tree-ring materials were collected from sites ca 20 km northeast (Aura; 60°36’N 22°33’E) and ca 20 km southwest (Parainen; 60°19’N 22°06’E) of the City of Turku, visited in November 2020 and in October 2019, respectively (Fig. 1). The collection of this material has previously been published and described by Helama (2022). In practice, the search for old-growth trees resulted in sampling sites with well-drained terrains on coarse mineral soils and occasional bedrock outcrops, where trees had not for long time been harvested, assumingly due to relatively rough accessibility. Tree-ring samples were extracted from fifteen trees under the licence of landowners, using Haglöf increment borer at a breast height (1.3 m). One radius per tree was cored. Ring widths were measured similar to archaeological materials, on the cross-section of the bore samples, to the nearest 0.01 mm under the light microscope. Cross-dating of this tree-ring material was performed both visually and statistically (Holmes, 1983). The living-tree and archaeological tree-ring data were processed using identical techniques to maintain comparability. That is, the ring-width series were transformed into dimensionless indices using the 32-year spline function and the resulting index series were pre-whitened (Cook and Peters, 1981; Cook *et al.*, 1990a, 1990b). The pre-whitened index series were averaged into the mean chronologies. Tree-ring series representing the Turku site were averaged and used as a local reference for the archaeological tree-ring data. The series of all the three sites were averaged into a regional chronology for additional comparisons.

Hereafter, the tree-ring data comprising the site and regional living-tree and archaeological chronologies are referred to as SITE, RGNL and ARCH data, respectively.

Climatic analyses

Long-term instrumental climate records, available from the Turku meteorological station (Tuomenvirta *et al.*, 2001), were used to illustrate the growth/climatic relationships in tree-ring data. Monthly mean temperatures and precipitation sums are available from the Turku station since 1909. However, these records appeared discontinuous over the 21st century and the monthly values were updated from the spatial model of Aalto *et al.* (2013, 2016) from 2000 onwards. Pearson correlations between the linearly detrended meteorological records and tree-ring index series were calculated over the 1910–2019 period, and separately over the early (1910–1964) and late (1965–2019) periods.

Chronology statistics

Replication curve of the new Turku chronology was used to portray temporal variations in sample materials. The mean inter-series correlation was calculated as a measure of the strength of the common growth signal within the chronology (Briffa and Jones, 1990). Expressed population signal (EPS; Briffa and Jones, 1990) was used as indication of chronology reliability. The EPS measures the expression of common variability among the available tree-ring series through time. A commonly accepted level of EPS > 0.85 was obtained as a criterion for an acceptable level of chronology confidence (Wigley *et al.*, 1984). That is, tree-ring chronologies with EPS higher than 0.85 have been shown to perform satisfactorily over the calibration and verification periods when evaluating the climate/growth relationships statistically (Helama *et al.*, 2017a). Comparison of the mean inter-series correlations were quantified using the *t*-test. The Fisher's z transformation (Fisher, 1921; Ruxton, 2006) was applied to the correlation coefficients (r) between the tree-ring index series, prior to estimating p-value for the *t*-test. This procedure followed the previously suggested approach (Helama *et al.*, 2016) to statistically characterise mean values for two groups of r in dendroclimatic studies.

Tree-ring variability was also characterized using the standard deviation and the mean sensitivity (Fritts, 1976), calculated from the tree-ring index series. Moreover, growth rates (mm/year) were calculated from the series of ring widths. Since the archaeological samples contained less rings than the living trees sampled for this study, this analysis was carried over the 100 innermost rings in the case of both the archaeological and living-tree samples. Tree-ring growth patterns related to trees' age were illustrated by aligning the tree-ring width series according to their ring number (counted from the innermost ring) and obtaining mean curves for the living-tree and archaeological tree-ring data.

RESULTS

Archaeological tree-ring data

In total, 34951 rings were measured. Mean length of the sample series was 101.9 years. Ninety, fifty and ten percent of the series were at least 53, 88, 160 years long, respectively. The longest series contained 324 rings. Twenty-seven of the series contained less than 50 rings. Widths of the tree rings were on average 1.13 mm, their 90th and 10th percentiles being 2.68 and 0.25 mm, respectively.

Sixty series were dated against the existing master chronologies. The ARCH series appeared more frequently dating with the Åland chronology (n = 38) than with the Tavastia chronology (n = 12). Only three series dated against both existing chronologies. Thirteen series not dated against either of the two chronologies were additionally dated against the mean of them.

Subsequently, 48 series were dated against the developing Turku master chronology and were included in the developing dataset. Using this new chronology, twenty additional series were dated and were also included in the Turku chronology. Finally, the ARCH chronology of Turku contained 128 tree-ring series from altogether 91 sample disks (Fig. 2A; Table 1).

Replication curve illustrated that the material could be divided, based on their chronological position, into the medieval and more recent samples (Fig. 2B). That is, the data

Table 1. Archaeological excavation sites in Turku and the number (n) of tree-ring dated samples.

Title of excavation report	n
Turku Åbo Akademi kaivaukset	17
Turun kaupunginkirjaston kaivaukset	9
Turku Itälaituri 2008	6
Varhaisinta Turkua -kaivaus	5
TMM20764 HJ89 vanhin rakennus	5
TMM14740 Valosen D-rakennus	5
Raatihuone, alue 4, rak 4	8
Rettiginrinne	4
Nunnankatu 4	4
Tontti Turku I/1/6 kaivaukset	3
TMM20764 HJ89 nuorempi rakennus	3
Puurakennus, kaivaus 3	3
Puurakennus, kaivaus 1	3
Raatihuone, kellari 2 SE-s.	2
TMM20315 RH86 al.4, rakennus AD1320	2
TMM18667 Akatemian puist. rak. A	2
Varhaisinta Turkua -kaivaus	1
Nunnankatu	1
2010 kaivaukset	1
TMM20764 HJ89 nuorin rakennus	1
TMM20671 UM688 vanhempi rakennus	1
TMM20671 UM688 nuorempi rakennus	1
TMM20315 RH86 al.5, rakennus AD1475	1
TMM20315 RH86 al.4, rakennus AD1400	1
TMM18667 Akatemian puist. rak. B	1
Kirkkopiha, Linnankatu 3	1

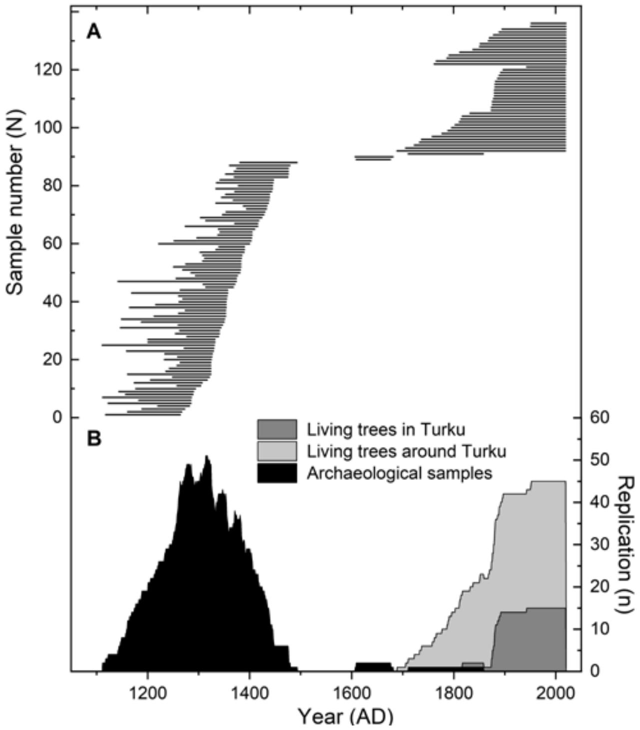

Fig. 2. Temporal distribution of tree-ring dated samples. Chronological position of the samples (N) represented by a horizontal bar, with length equal to the number of annual rings (A), with replication of the chronology (n) shown as sample size per year for archaeological and living-tree samples from Turku and other sites (B).

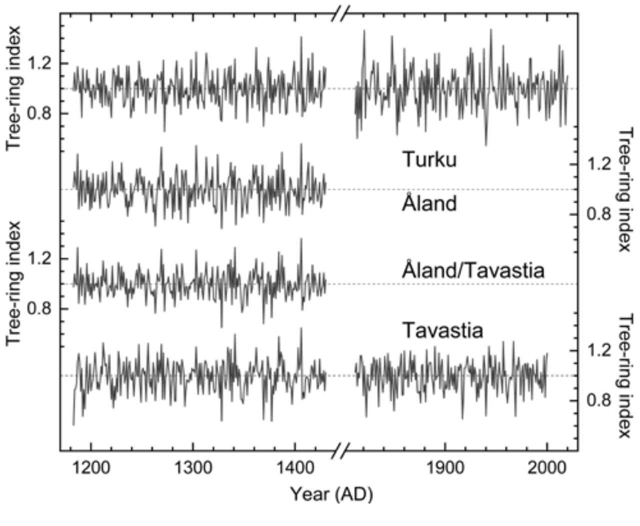

Fig. 3. Tree-ring chronologies. Pine growth variability illustrated by tree-ring data representing the Turku region, Åland Islands, Åland and Tavastia, and Tavastia. The chronologies are shown over the medieval (1183–1430) and recent (1812–2020) periods, when the expressed population signal (EPS) exceeded the 0.85 level of an acceptable level for chronology confidence, in the case of Turku data.

started to accumulate around the first decades of the 12th century. The ARCH chronology contained highest number of samples around the mid-13th to mid-14th century. Moreover, the curve declined towards the end of the 15th century. There appeared a gap of data from the last decade of that century until the mid-16th century. Since that date, the chronology contained only a small amount of tree-ring series until the 19th century. The medieval part of the chronology cover the years between 1110 and 1493.

The ARCH chronology portrayed pine growth variations on inter-annual to longer timescales (Fig. 3). The EPS-statistic exceeded the 0.85 level between the years 1183 and 1430. Over this period, the ARCH chronology correlated with those of Åland and Tavastia (see Fig. 3) with coefficients of 0.659 and 0.463, whereas the correlation with the mean of Åland and Tavastia chronologies was 0.675.

Living-tree chronologies

The SITE and RGNL chronologies exhibited markedly varying growth on short and longer scales (Fig. 3). The SITE data cover the years between 1815 and 2019, the RGNL data spanning the 1688–2020 period. Sample size (i.e., replication) of the SITE chronology was diminished prior to 1880s (Fig. 2B), before which date the replication of the RGNL chronology, too, was relatively low.

For the SITE chronology, the EPS > 0.85 criterion was reached between the years 1885 and 2019. The same threshold for the RGNL chronology was obtained since 1812. This means that no reasonable comparison between the most recent segment of the ARCH and the oldest segment of the SITE/RGNL chronologies could be made (there is only one tree in each chronology over their overlapping period). Over the 1812–2000 period, the RGNL chronology and that of Tavastia were correlating with r = 0.437.

Tree growth was related to climatic factors over the instrumental 1910–2019 period (Fig. 4). Strongest correlations were found with early-summer precipitation and winter temperatures. Trees had responded positively to January–March temperatures indicating that warm temperatures during the dormancy were advantageous to these trees, whereas cold temperatures during these months have led to diminished growth during the following growing season. In the case of both the SITE and RGNL chronologies, this response appeared stronger over the early period (1910–1964), with markedly high correlations especially for January and February (Fig. 4B). Positive correlations to May through August precipitation (Fig. 4A–B) indicated that pine growth had benefitted from increased summer precipitation. Also this response appeared more pronounced over the early period (1910–1964), both for SITE and RGNL data, in comparison to the late half of the instrumental period (1965–2019).

Overall, pine growth correlated stronger with summer (June–July) precipitation sums than with winter (January–March) mean temperatures. Moreover, the correlations with June through July precipitation were stronger for RGNL rather than the SITE chronology. Calculated over the full instrumental period (1910–2019), the connection between the pine growth and summer precipitation was characterised by $r = 0.400$ ($p < 0.001$) and $r = 0.490$ ($p <$

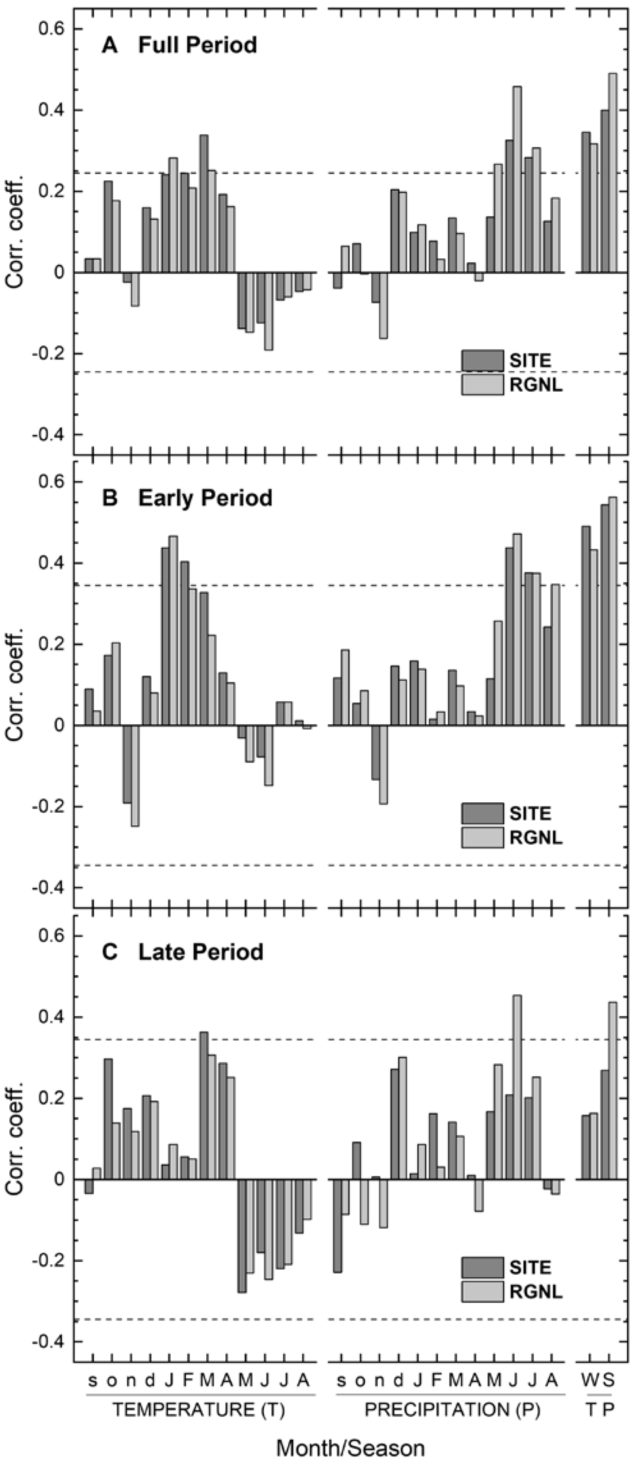

Fig. 4. Pine growth response. Climatic associations were calculated as Pearson correlations of the site (SITE) and regional (RGNL) chronologies to monthly mean temperatures and precipitation sums of previous (with a lower-case letter) and concurrent year of growth (with an uppercase) over the full instrumental period (1910–2019) (A), early period (1910–1964) (B) and late period (1965–2019) (C). The uppercase letters W and S stand for seasonal correlations to winter (January–March) temperature and summer (June–July) precipitation. Horizontal dashed lines represent the level of significance $p < 0.01$. Dark and light grey columns represent the site (SITE) and regional (RGNL) chronologies, respectively.

0.001), in the case of the SITE and RGNL chronologies, respectively.

Comparison of tree-ring statistics

Statistics of tree-ring growth are presented in Fig. 5. The mean inter-series correlation among the SITE data was 0.326, whereas the same estimate for the RGNL data was 0.267, indicating that the growth variability was more similar among the SITE than RGNL series. Moreover, the *t*-test between these correlations indicated that their difference ($\Delta r = 0.059$) was statistically significant ($p < 0.001$). The mean inter-series correlation in the ARCH data was 0.258. It appeared that the difference between the correlation of ARCH and SITE data ($\Delta r = 0.068$) was statistically significant ($p > 0.001$), however, no such difference was found ($p > 0.05$) between the ARCH ad RGNL data ($\Delta r = 0.009$).

Growth rates of the SITE and RGNL trees averaged 1.60 mm and 1.16 mm, respectively, these values falling below and above that of the ARCH data (1.28 mm). Among these figures, the difference between the ARCH and SITE data was found to be statistically significant ($p < 0.01$). Comparison of growth curves showed that this difference

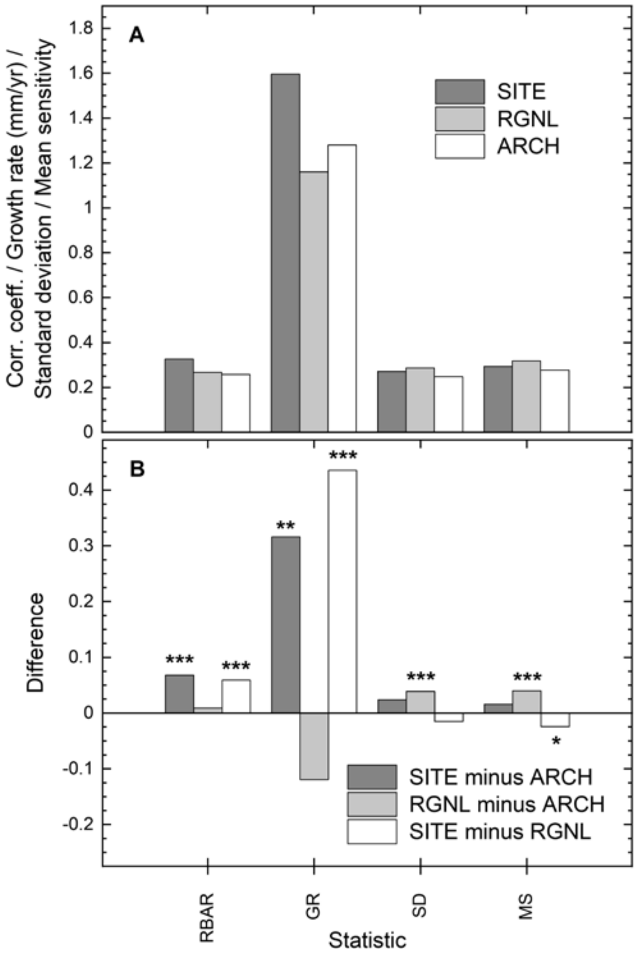

Fig. 5. Characterization of the tree-ring data. Growth patterns were quantified using the individual series from site (SITE) and regional (RGNL) living-tree and from archaeological (ARCH) chronologies using the inter-series correlation between the series (RBAR), growth rate (GR, mm/year), standard deviation (SD), the mean sensitivity (MS) (A), and the difference in the mean levels of the same statistics between the three types of data series (S, R, and A), calculated as subtraction (B). Statistical significance (*t*-test) at levels $p < 0.05$, $p < 0.01$ and $p < 0.001$ are denoted by one (*), two (**) and three (***) asterisks, respectively.

resulted from an increased growth in the SITE series over their first 50 years (Fig. 6).

Standard deviations of the SITE and RGNL tree-ring index series were, on average, 0.272 and 0.287, respectively (Fig. 5). The corresponding value of the ARCH indices was 0.248. The difference between the corresponding ARCH and RGNL values was found to be statistically significant with ($p < 0.001$). Similarly, the difference between the mean sensitivity of RGNL (0.318) and ARCH (0.278) indices was found to be statistically significantly ($p < 0.001$). The difference between the SITE and RGNL mean sensitivities, albeit weaker, was also statistically significant ($p < 0.05$).

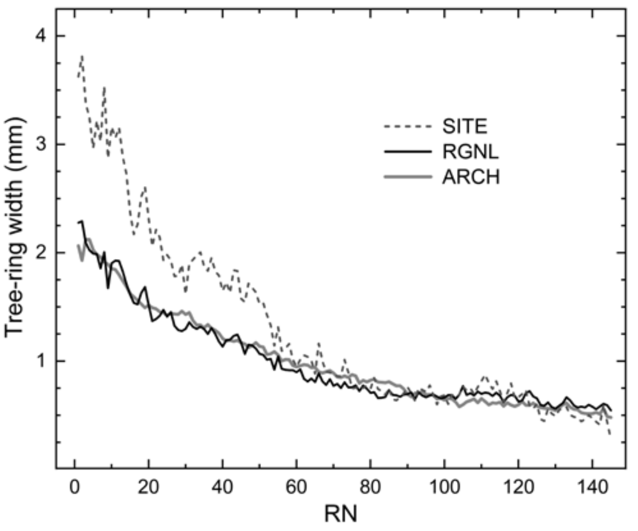

Fig. 6. Age-related changes in the series of tree-ring width obtained from site (SITE) and regional (RGNL) living-tree and archaeological (ARCH) chronologies, illustrated as a function of ring number (RN).

DISCUSSION

The Turku chronology developed in this study represents sites where no such long tree-ring record have been previously presented and published. In the areas around the Baltic Proper, living-tree chronologies built previously from Scots pine (*Pinus sylvestris*) tree rings have been similarly extended back in time using pinewood samples from historical buildings (Bartholin, 1991; Zetterberg, 1991; Vitas, 2008; Zielski *et al.*, 2010; Savolainen *et al.*, 2023). Moreover, subfossil samples unearthed from natural archives of south boreal forested ecosystems have been used to construct late Holocene tree-ring chronologies (Lindholm *et al.*, 1998–1999; Helama *et al.*, 2005, 2017b). Most of these chronologies are millennial or near-millennial in their length (Läänelaid *et al.*, 2012). In addition to dating, these records have so far been used as proxy data for reconstructions of past temperature and moisture variability from local to even hemispheric scales (Esper *et al.*, 2002; Helama *et al.*, 2009; Seftigen *et al.*, 2013, 2015, 2017; Cook *et al.*, 2015; Balanzategui *et al.*, 2018; Przybylak *et al.*, 2020).

Regarding our regional dataset, the ARCH chronology correlated more strongly with the Åland chronology, despite the shorter distance between Turku and the Tavastia site (see Fig. 1B). With these regards, the Åland chronology was built from construction wood (Fig. 1C) whereas the samples comprising the Tavastia chronology originate from a wet riparian zone adjacent to the lake (Fig. 1F) on which the trees now forming the subfossil assemblage once grew. Likely, the positive response to warm-season precipitation, in the Åland and SITE/RGNL chronologies, can be used to explain the connection. This climatic factor was found to be the most evident determinant of *P. sylvestris* growth in Turku (Fig. 4) and in the Åland Islands (Helama and Bartholin, 2019). In terms of palaeoclimatology, we note that the previously developed Old World Drought Atlas, being a series of year-to-year maps of gridded, tree-ring-based reconstructions of summer moisture conditions over Europe and the Mediterranean Basin (Cook *et al.*, 2015), does not contain any data from the study region. It is anticipated that the developing datasets from this region could in the future be used to detail the spatial picture of the hydrological anomalies in Europe and adjacent areas, and to better understand the spatiotemporal variability of moisture patterns through the late Holocene times.

In addition to precipitation signals, SITE/RGNL chronologies correlated with winter temperature (Fig. 4). Similar correlation was as previously demonstrated, with differing strengths, also for the Tavastia and Åland chronologies (Helama *et al.*, 2014; Helama and Bartholin, 2019). These results concur with an analysis by Läänelaid *et al.* (2012) who showed that the strength of the correlations between the long *P. sylvestris* chronologies from Estonia, Sweden, Finland, Lithuania, Poland and NW Russia increased in times when winter westerlies enhanced (Trouet *et al.*, 2009), this circulation pattern bringing mild, moist Atlantic air masses onto the region (Hurrell, 1995). In the areas around Baltic Proper, similar, positive relationship of *P. sylvestris* tree-ring growth to January temperature has been demonstrated with increased strength over the recent decades (Harvey *et al.*, 2020). In our data this relationship was reducing from early to late instrumental period, suggesting that the factors behind the signal may be complex.

Thus far, the Turku chronology spans over ten centuries, however, with low replication between the medieval and recent segments. In this regard, two potential sources of additional tree-ring materials could be considered. First, the old-growth trees growing in or near the City of Turku could be further surveyed. In southern Finland, however, the number of old-growth trees (≥ 150 years) is limited compared to the northern part of the country, as a higher human population density and more intensive land use have had relatively more detrimental effects on the southern forests (Henttonen *et al.*, 2019). Using the EPS > 0.85 criterion (Wigley *et al.*, 1984), there is a need to enhance the chronology confidence before 1812. Practically, such a target would require sample trees older than 200–250 years. The task of finding such old trees is not alleviated by the fact that, in Finland, the large majority of old trees are in fact known to be relatively small in diameter (Henttonen *et al.*, 2019). Second, there is a limited number of historical wooden buildings surviving in Turku from before the 1800s, the watershed in this respect being the Great Fire of Turku in 1827, which destroyed nearly three quarters of the town. Potential locations do exist, especially in the open-air Handicraft Museum, the area which was situated on the outskirts of the town at the time of the fire (e.g. Seppänen, 2018), or the Qwensel house (Savolainen *et al.*, 2022). That the ARCH data showed inter-series correlations similar to RGNL data could also suggest that inclusion of historical tree-ring samples from buildings with similar distances (ca 20 km) from Turku should not violate the chronology statistics in terms of its local climatic signals. That is, historical tree-ring samples from Turku surroundings could potentially be used to increase the replication of the chronology over the pre-19th century era. With these regards, the findings also suggest that the tree-ring materials now forming the ARCH chronology were not harvested from any restricted hypothetical "Turku site" but more likely represent trees and their growing conditions around Turku.

Updating archaeological and historical tree-ring chronologies with living-tree data is an essential but not necessarily a straightforward task. The main issue concerns the compatibility and balance between the two data assemblages. The main discrepancy between the two is that while the living-tree data are commonly sampled from carefully selected sites and trees following the dendrochronological principles (LaMarche, 1982; Schweingruber *et al.*, 1990), the ancient wood was once utilised by contemporaries according to their own needs and criteria. According to Tegel *et al.* (2010), this caveat could be circumvented by a random sampling of modern wood, for which purpose their collection of recent tree-ring data was produced from samples from sawmills and lumberyards scattered over the region of their own historical oak data. Similar approach was later applied to a collection of pine tree-ring data (Helama *et al.*, 2017a) obtained from saw logs for that had been rail-transported from the Novgorod region (NW Russia) (Hautamäki *et al.*, 2010), to be analysed with the medieval Novgorodian tree-ring chronology (Kolchin, 1967). It was found, however, that the growth rates of the modern saw logs markedly exceeded those of the medieval timber and that comparable datasets of the recent and medieval tree rings could not be derived unless the data was standardized with pre-whitening (Helama *et al.*, 2017a). Intriguingly, the method of sampling random trees (as Tegel *et al.* (2010) suggested) did not result in fully comparable datasets. While these results could at first glance be seen to concur with several forestry studies conducted since the seminal work by Cherubini *et al.* (1998), showing that the classical dendrochronology-oriented selection of trees and sites could bias the tree-ring based growth estimates in comparison to data of randomly selected trees (e.g. Klesse *et al.*, 2018), such findings may not be straightforwardly relevant to our results but require further discussion. In what follows, we suggest some issues that could be raised.

First, the growth curves of ARCH series were actually found to be surprisingly similar to the RGNL curve (Fig. 6). Since particularly the RGNL data was correlating more strongly with summer precipitation than with winter temperatures, the finding could imply that not only the RGNL but also the ARCH trees were drought-stressed and for that reason more slowly growing. By contrast, the SITE curve differed from RGNL and ARCH curves, with notably high growth rates over the first decades of trees' lifespan, this early growth phase then leading to statistically significant difference between the growth rate estimates (Fig. 5). Deviation of this type is most likely related to the conditions and history of the site. Stronger decline after the early phase of faster growth, similar to the SITE curve with more concave curvature (see Fig. 6), could indicate conditions with relatively high tree density at a young age in the stand, after which the competition between the trees has led to a progressive narrowing of ring widths (Mikola, 1950). Possibly, the trees of the SITE chronology originate from a forest that during the 1800s represented such a high-density site. As an additional and more hypothetical explanation, it is also noteworthy that long-term positive response of stem growth to wood ash has been recorded for *P. sylvestris*, especially given that availability of nitrogen suffices (Saarsalmi *et al.*, 2014). Tentatively, such effects from wind-blown ash could have had consequences in the early phase of the site due to its close proximity to the large areas burned in the Great Fire of Turku in 1827. Overall, the comparisons show the benefits of building the chronology from data representative of multiple tree-ring sites, thus avoiding the influence of site-specific growth reactions.

Second, the recommended method of standardization to produce compatible data assemblages (i.e., pre-whitening) was applied to our tree-ring series, but the ARCH and RGNL indices did not appear completely standardized in terms of their growth amplitudes, that appeared more ample for the living-tree data. Although this difference was not large, it was statistically significant (Fig. 5) and even discernible between the ARCH and RGNL chronologies of Turku (see Fig. 3). Two alternative explanations could be proposed. The observed difference may reflect change in climate variability from medieval to recent times. However, no similar change from medieval to recent period is discernible in the Tavastia chronology (see Fig. 3), suggesting a role of other factors, such as edaphic conditions that are known to affect the growth amplitudes in tree-ring data (Fritts, 1976). With these regards, tree-ring samples of the RGNL chronology were collected mostly from terrains on drained soils where old-growth pines could at present be found (Fig. 1E), whereas the origins of the trees forming the ARCH chronology remain unknown. These findings constitute a challenge to the future sampling strategies. Focussing on more mesic habitats, to mimic a set of sites where medieval actors (according to this hypothesis) harvested their timber, would most likely result in samples of predominantly young pines. Unfortunately, such a sample assemblage would extend the temporal gap between the archaeological and living-tree chronologies. Again, this consideration sets the stage for tree-ring sampling of timber from historical buildings.

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