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Dendroclimatic signals in Scots pine tree-ring chronologies in southwest Finland

Samuli Helama

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Abstract. Tree rings provide palaeoclimatologists with well-dated, high-resolution proxy archive for reconstructing past climate variability. New tree-ring data were developed from Scots pine trees from archipelagic, intermediate, and mainland sites in the Turku region, southwest Finland. The dominant climatic variable affecting the growth of Scots pine trees was late-spring/summer precipitation. Tree growth responses to other variables representing climatic conditions outside the growing season were found to be more variable between the sites. Chronology variance and correlation between tree-ring series were the highest and correlation with the growing season precipitation was the strongest at the archipelagic site. Regression models were developed to evaluate the palaeoclimatic potential of dendrochronologic archives from the Turku region. These models explained ~ 30% of the variance in instrumentally observed precipitation. Climatic correlations and verification statistics showed a reasonable reconstruction skill and suggest a potential for new tree-ring reconstructions of the past precipitation variability and hydroclimatic events in southwest Finland.

Keywords: *Earth Sciences; palaeoclimatology; dendrochronology; precipitation*

Samuli Helama (samuli.helama@luke.fi), https://orcid.org/0000-0002-9777-3354, Natural Resources Institute Finland, Ounasjoentie 6, 96200 Rovaniemi, Finland

INTRODUCTION

Palaeoclimatic research employs indirect (proxy) estimates of past climate, which are climate-sensitive series of geological, glaciological, or palaeontological records, as well as archaeological or historical archives (Bradley 1999). Tree-ring chronologies and associated paleo-environmental data provide the potential to assess tree growth and analyse climatic determinants of growth variability. Furthermore, they allow to date historical, archaeological, and subfossil tree-ring materials, and to reconstruct past climate variability (Briffa *et al*. 2004; Haneca *et al*. 2009; St. George 2014).

The tree-ring data for this study were collected from a number of sites ranging from archipelagic to more mainland ones in and around the Turku region. There are several reasons why this study focused on these materials. First, the archaeological excavations conducted in Turku have uncovered a large number of wooden artefacts, including construction timber representing pinewood materials (Zetterberg 2003; Seppänen 2012), which may provide a previously unexplored dendrochronological data source for palaeoclimate research. Thus, analysis of the climate-growth relationships of living trees may also help understand the value of the archaeological tree-ring materials, i.e., the living tree data may serve as modern analogues of dendroclimatic correlations with instrumental climate data (Tegel *et al.* 2010; Helama *et al.* 2017).

Secondly, southwest Finland is a region where tree-ring data of Scots pine trees have not been intensively studied. Previously, Karlsson (2009) reported that Scots pine tree-ring growth could be related to June precipitation and July temperature in the Satakunta region, ~100 km north of the present study. Moreover, Helama and Bartholin (2019) found a similar Scots pine response in southwestern Finland, in the Åland Islands. However, their investigation was based on tree rings from historical timber and climatic data from the 18th century weather observations (Holopainen 2004,

2006) and, as a consequence, did not information on the recent climate-growth relationships. Henttonen *et al.* (2011) analysed Scots pine tree-ring data across Finland and Estonia but none of them were from the Turku region. More recent studies focused on tree-ring data of the same species from the sites northeast of the Turku region (Helama *et al.* 2014; Matisons *et al.* 2021) and thus could not serve as modern updates of the archaeological tree-ring materials from Turku.

Thirdly, it has been recently shown that one of the earliest dendrochronological/dendroclimatic investigations in Europe was carried out by Johan Leche and took place in Turku during the 1750s (Norrgård, Helama 2021). Since then, the tree-ring data of nearby forests have not been more intensively studied.

The purpose of this study is to develop a new Scots pine (*Pinus sylvestris* L.) tree-ring database for southwest Finland (Fig. 1), to assess the growth variability of this tree species and its climatic determinants in this region, and to demonstrate the value of these data for high-resolution palaeoclimatic research. The present work aims to contribute to the long tradition of tree-ring research in Finland at the very root of dendrochronology.

MATERIALS AND METHODS

Physical setting

Tree-ring data were collected from three sites in southwest Finland, along a 40-km-long transect near the Baltic Sea (Fig. 1). The site locations form a transect, which is oriented approximately from southwest to northeast, from archipelagic conditions to the more continental ones. That is, the site in Parainen is located ~ 20 km southwest of the site in Turku, whereas Aura site is ~ 20 km northeast of Turku (Fig. 1). The sites represent well-drained terrains, pine-dominated stands on coarse mineral soils and occasional bedrock outcrops, with a thin humus layer. This region belongs to the hemiboreal vegetation zone (Ahti *et al.* 1968). In this study, the Parainen, Turku, and Aura sites are referred to as archipelagic (ARCH), intermediate (INTM) and mainland (MNLD), respectively (Fig. 1B).

Tree-ring data

Tree-ring samples were extracted from Scots pine (*Pinus sylvestris* L.) trees under the licence of landowners, using Haglöf increment borer at a breast height (1.3 m) to achieve ring-width samples from 15 trees at each site (one radius per tree). The fieldwork was carried out in October 2019 (ARCH and INTM sites) and November 2020 (CONT site). Ring widths were measured on the cores to the nearest 0.01 mm under the light microscope. Dendrochronological cross-dating was performed both visually and statistically (Holmes 1983).

Long-term growth variations attributable to biological factors were removed from the tree-ring series using a two-phase (i.e., double) detrending technique. First, the long-term trends pertaining to the tree ageing were eliminated from each tree-ring series. This was done by fitting either a modified negative exponential curve or a regression line with a negative or a zero slope (Fritts 1976) to the series of ring widths, and thus obtaining tree-ring indices as ratios between the measured growth values and the value of the curve. Second, a spline curve (Cook, Peters 1981) was fitted to the series of ratio-based indices. The growth variations captured by this curve were removed from the data by dividing the ratio-based index value by the value of the spline curve. A previously suggested rigidity of the spline (see Cook *et al.* 1990a) was used to represent two-thirds (67%) of the length of each series (50% frequency response cut-off). Furthermore, the series of tree-ring indices from the second detrending were pre-whitened to remove the autocorrelation from the series (Cook *et al.* 1990b). The cross-dated index values were averaged to produce mean site chronologies using a bi-weight robust mean (Mosteller, Tukey 1977; Cook *et al.* 1990b).

Tree-ring variability was characterized using the first-order autocorrelation, standard deviation, and the mean sensitivity (Fritts 1976) of the site chronologies. Moreover, the mean correlation among the series of individual tree-ring index series (Briffa, Jones 1990) and the expressed population signal (Wigley *et al.* 1984) were used for characterising the chronologies. These statistics were calculated for the 1960–2019 period that is common to climatic data (see below). Along with the variance explained by the first principal component, these have been previously used to characterise the tree-ring data representing various types of settings (Carrer, Urbinati 2004).

Climatic data

The climatic variables that affected pine growth were revealed using bootstrapped response function analyses. This method produces coefficients (computed between the tree-ring chronology and the series of monthly temperature and precipitation variables) as multivariate estimates (Biondi, Waikul 2004). The series of monthly climatic data were linearly detrended before conducting dendroclimatic analyses by fitting a regression line to each monthly record of temperature and precipitation values and then extracting the trendline from the series by subtraction. Response functions were computed separately for the pre-whitened ARCH, INTM and MNLD chronologies. The climatic data for each tree-ring site were obtained

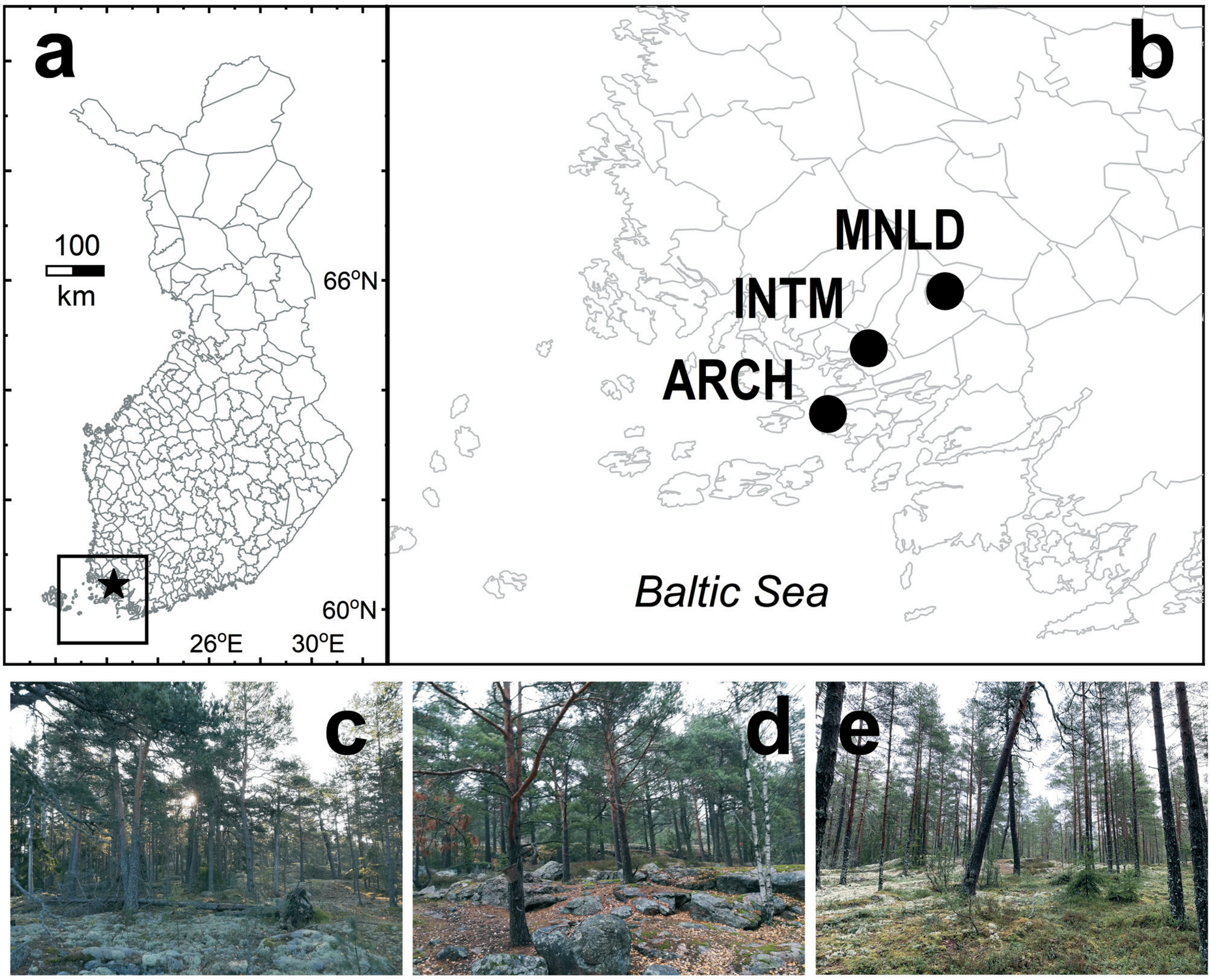

Fig. 1 Map of Finland, with the study region indicated by a rectangle, and location of the City of Turku indicated by a star (a). The inlet (b) indicates locations of archipelagic (ARCH) (c), intermediate (INTM) (d), and mainland (MNLD) (e) sites in southwest Finland

from the spatial model built using the monthly mean temperatures and monthly precipitation sums (total amount of rain) collected by the Finnish Meteorological Institute, and subjected to kriging interpolation to account for the influence of topography and water bodies, since 1960 (Aalto *et al.* 2013, 2016).

Longer instrumental climate records were available from the Turku meteorological station (Tuomenvirta *et al.* 2001). Monthly precipitation sums are available from this station since 1909 but the record appears discontinuous over the 21st century. Here, the monthly precipitation sums were updated by the corresponding values obtained from the spatial model (Aalto *et al.* 2013, 2016) from 2000 onwards. These data were used to test the temporal stability of the relationship between proxy (i.e. tree-ring) data and climate. Linear regression was computed for the calibration period, which was the same as the one used for the original climatic correlations (1960–2019). Dendrochronological and climate data (1909–1959) withheld from the calibration were used to assess the veracity of the climate/proxy relationship with independent data (verification period; Fritts 1976). Pearson correlations between the observed and reconstructed values were calculated over the calibration and verification periods. Reduction of error (RE) and coefficient of efficiency (CE) statistics were calculated over the verification period. Positive RE and CE were used to indicate real skill in the reconstruction (Fritts 1976; Briffa *et al.* 1988). All the dendroclimatic analyses described in this section were carried out using pre-whitened tree-ring data.

RESULTS

Tree-ring chronologies

The ARCH, INTM, and MNLD chronologies cover the periods 1688–2019, 1815–2019 and 1761–2020, respectively. Tree-ring width chronologies from the archipelagic (ARCH), intermediate (INTM) and mainland (MNLD) sites portrayed growth variations on different scales varying from inter-annual to longer ones (Fig. 2a–c). Both visual comparison and Pearson correlations between the chronologies showed fairly similar pine growth variability, although dissimilarities there appeared as well. That is, the correlations calculated (1960–2019) between the MNLD and INTM chronologies, and between the MNLD and ARCH chronologies, were r = 0.283 and r = 0.294, respectively. For pre-whitened data, the respective correlations were r = 0.354 and r = 0.315. By contrast, the correlation between the ARCH and INTM chronologies was as high as r = 0.565 (r = 0.548 for pre-whitened data). These correlations suggest that the connections between the chronologies were not so much dependent on the distance between the sites as on their distance to the Baltic Sea.

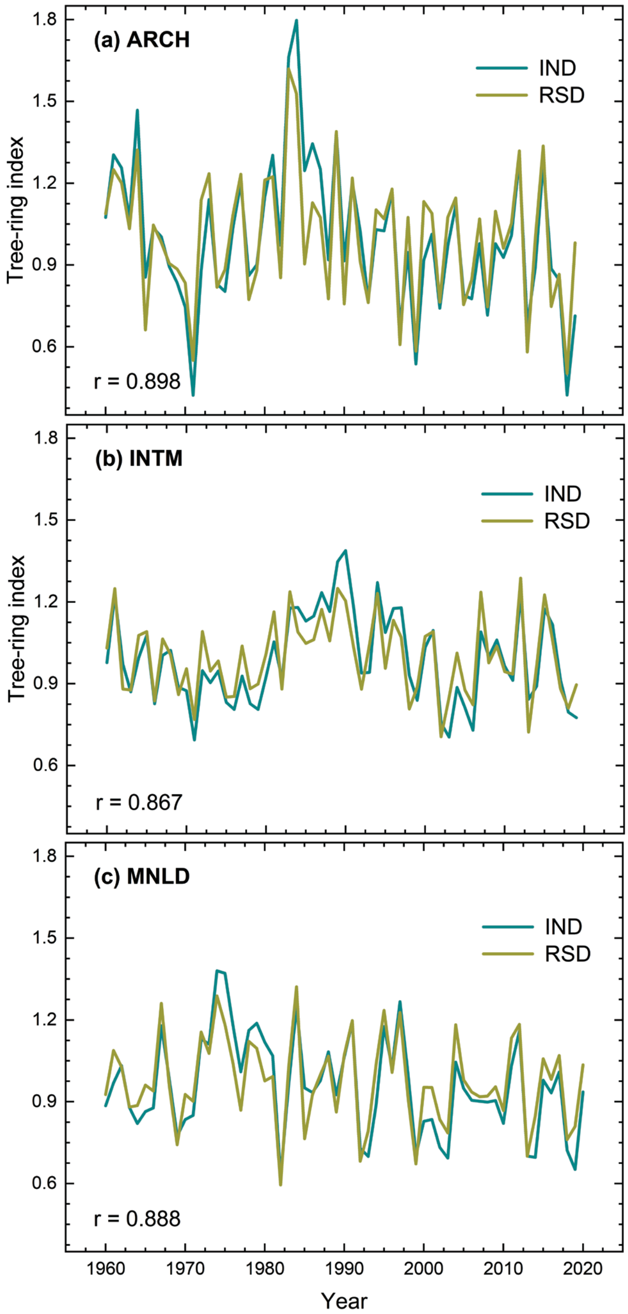

Fig. 2 Archipelagic, intermediate, and mainland (ARCH, INTM and MNLD) site chronologies produced using the double detrending (IND) and pre-whitening (RSD). The chronologies are shown since 1960 when they were analysed with climatic data

Tree-ring statistics

All the statistics except the first-order autocorrelation showed a change from the ARCH site towards the INTM/CONT sites (Fig. 3). These changes, in mean sensitivity and standard deviation, demonstrated ampler growth fluctuations at the ARCH site, in comparison to INTM and MNLD sites. Correlations between the trees and the variance explained by the first principal component showed that similarity in growth patterns between individual trees was the highest at the ARCH site and the lowest at the MNLD one. As a result, the expressed population signal (EPS) reached the highest score at the ARCH site and the lowest one at the MNLD site. This statistic reached the EPS > 0.85 criterion for the ARCH and INTM sites, whereas for the MNLD site the EPS-statistic remained slightly below that threshold (see Fig. 3). This finding implies that the sample size of fifteen trees may remain suboptimal for that site and that at least irregular results (if any) obtained for the MNLD site ought to be treated with caution.

Climatic connections

Correlations with climatic records indicated that growth variability was predominantly related to variability in precipitation parameters (Fig. 4a–c). The climate-growth correlations calculated for the 60-year period (1960–2019) showed that at the ARCH site, pine growth responded positively to May and June precipitation. Pines from other sites showed similar responses to June precipitation. In addition, they also showed a positive response to July precipitation (INTM) and March temperature (INTM), and a negative response to October (MNLD) precipitation (previous to the growth year). That is, there was a high similarity found between the significant factors for the three sites, which suggested that tree growth was predominantly controlled by summer precipitation. This connection was the strongest in the case of ARCH chronology with the response coefficient of ~ 0.4 to June precipitation, compared to INTM and MNLD chronologies that showed coefficients of ~ 0.3 to that variable. These findings were based on statistically significant correlations ($p < 0.05$) between the site chronologies and monthly climatic records. Interestingly, the ARCH chronology showed statistically significant connections only to growing season precipitation.

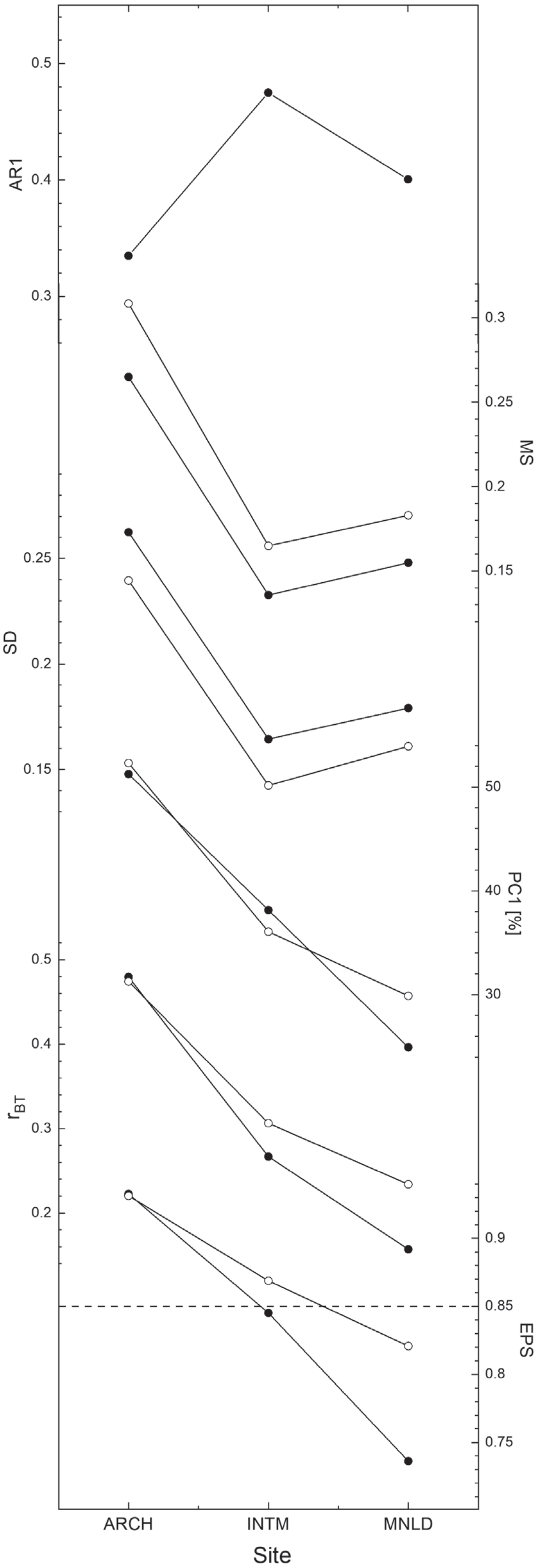

Fig. 3 Variation in chronology statistics (1960–2019) among sites. Comparison includes the first-order autocorrelation (AR1), mean sensitivity (MS), standard deviation (SD), variance explained by the first principal component (PC1%), correlation between the trees (r_{BT}), and the expressed population signal (ESP) calculated for the archipelagic (ARCH), intermediate (INTM) and mainland (MNLD) chronologies produced using the double detrending (filled symbols) and pre-whitening (open symbols).

Calibration and verification

Tree-ring data were used to reconstruct the late spring-summer (May–July) precipitation variability (Fig. 5). Alternative models were derived separately from simple linear regression based on the median (MD) and the first principal component (PC#1) of the

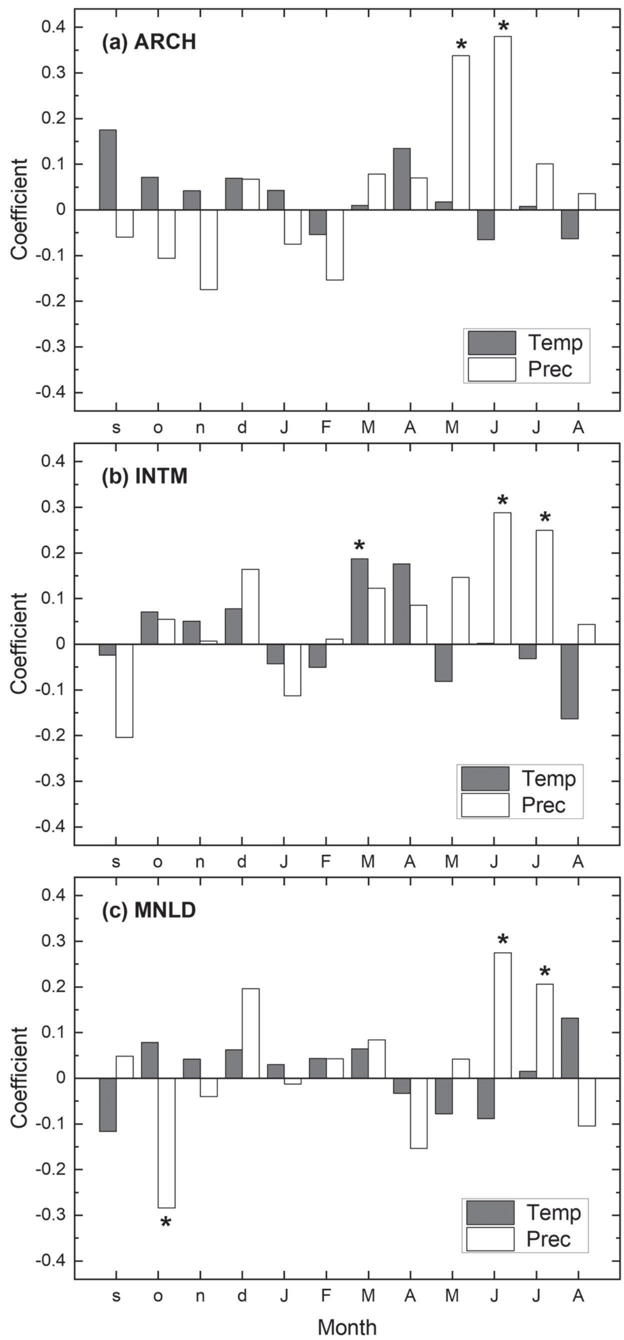

Fig. 4 Bootstrapped response analysis showing relationships between tree-ring chronologies and monthly mean temperatures and monthly precipitation sums (1960–2019). Chronologies of archipelagic (ARCH), intermediate (INTM) and mainland (MNLD) sites were separately compared to weather variables of the previous (small letters) and concurrent year (capital letters). Statistically significant relationships (0.05 level) are indicated by an asterisk

site chronologies and from multiple linear regression (MR) based on the three site chronologies. Correlations between the observed and reconstructed precipitation data vary around r ~ 0.55 during the calibration period (1960–2019). Very similar correlations were obtained for the verification period (1909–1959) (Table 1). These correlations were all statistically significant ($p < 0.001$).

Table 1 Calibration and verification statistics for the May–June precipitation reconstructions. Pearson correlations were calculated over the calibration period (r_{calib}) (1960–2019), verification period (r_{verif}) (1909–1959) and the full period (1909–2019) (r_{full}). Reduction of error (RE) and coefficient of efficiency (CE) statistics were computed over the verification period. Reconstructions were derived separately from simple linear regression based on the median (MD) and the first principal component (PC#1) of the site chronologies and from multiple linear regression (MR) based on chronologies at the three sites. All correlations are significant at $p < 0.001$ level

	r_{calib}	r_{verif}	RE	CE	r_{full}
MD	0.55	0.54	0.25	0.23	0.54
PC#1	0.54	0.57	0.26	0.24	0.54
MR	0.54	0.55	0.24	0.22	0.53

Moreover, the reduction of error and coefficient of efficiency statistics were positive for all the sites, indicating real skill in the reconstruction. That is, the data withheld from calibrations confirm the relationship that exists between the tree-ring and climate variability over the period originally used to highlight the climatic correlations (Fig. 4). Finally, the calibrations over the full period (1909–2019) resulted in reconstructions correlating with precipitation with r = 0.53–0.54, thus demonstrating that the models explain ca. 30% of the variance in instrumentally observed precipitation. As a further test of validity, the median of the site chronologies correlated with r = 0.64 with a historical May–June precipitation record (1750–1800) as previously published for Turku (Holopainen 2004). These results demonstrate the palaeoclimatic potential of Scots pine tree-ring chronologies from the Turku region and show that similar archives provide palaeoclimatologists with a high-resolution proxy data for the reconstruction of the past precipitation variability.

DISCUSSION AND CONCLUSIONS

Tree-ring statistics revealed a change in chronology variance, common growth signal, and climatic response along a transect from archipelagic site conditions to the more mainland ones. A similar gradient of change in tree-ring statistics from northeast to southeast Finland was demonstrated previously (Lindholm *et al.* 2000; Helama *et al.* 2005). In that case, which generally follows the classic framework of dendrochronological characterisation along biogeographical gradients (Fritts *et al.* 1965), higher correlations between individual tree-ring series in the

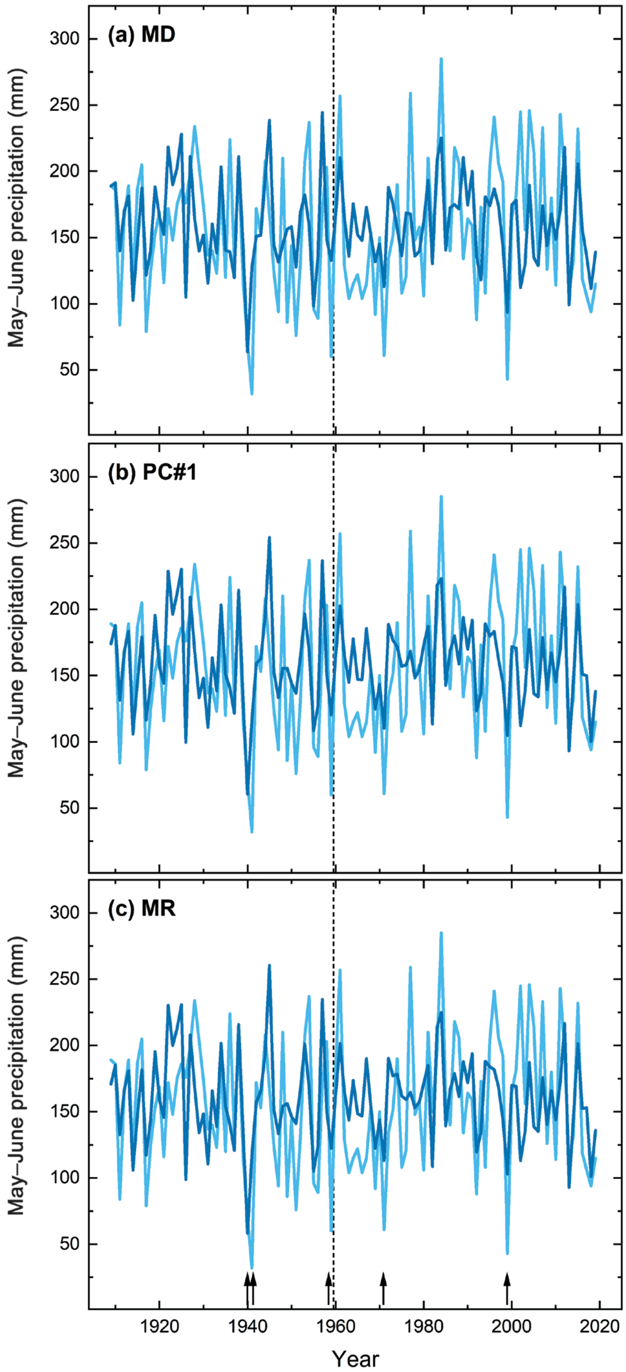

Fig. 5 Observed and reconstructed May–June precipitation histories (1909–2019). Reconstructions were derived separately from simple linear regression based on the median (MD) and the first principal component (PC#1) of the site chronologies and from multiple linear regression (MR) based on the three site chronologies. Observed (light blue line) and reconstructed (dark blue line) precipitation series are shown over the calibration (1960–2019) and verification periods (1909–1959). Five driest events based on instrumental data (1940, 1941, 1959, 1971, and 1999) are indicated by arrows

north were suggested to yield larger variance in the northern chronologies where the climatic control on pine growth was also strong. In southwest Finland, the strongest connection to summer (June) precipitation was evident in the case of the ARCH site (Fig. 4), where estimates of chronology variance and those of individual series similarity were higher than at the INTM and MNLD sites (Fig. 3). Collectively, these results demonstrate an increasing sensitivity to hydroclimatic factors, especially to June precipitation, towards the southwest (i.e., archipelagic site conditions) in the region.

Scots pine responses to late spring-summer precipitation, similar to those determined in this study, were previously reported from sites in Helsinki (Helama *et al.* 2012), southeast Finland (Lindholm *et al.* 2000; Helama *et al.* 2005), the Satakunta and Tavastia Proper regions (Karlsson 2009; Helama *et al.* 2014), the Åland Islands in south-western Finland (Helama, Bartholin 2019) and more generally in southern Finland (Henttonen 1984; Henttonen *et al.* 2011). Moreover, analysis of the network of tree-ring chronologies (Seftigen *et al.* 2015) also revealed similar responses of Scots pines from various sites and regions in Sweden (Linderholm, Molin 2005; Jönsson, Nilsson 2009; Seftigen *et al.* 2013). The above-mentioned network also contained the tree-ring chronology data of Norway spruce (*Picea abies* L.), and pedunculate oak (*Quercus robur* L.), the dendrochronological data of which were also shown to correlate with summer precipitation at sites around southern Finland and western Estonia (Mäkinen *et al.* 2001; Läänelaid *et al.* 2008, 2015; Helama *et al.* 2009a, 2014, 2016a, b, 2018; Läänelaid, Eckstein 2012; Sohar *et al.* 2014a, b). Moreover, *Tilia* spp. (linden) chronology was recently found to positively correlate with June precipitation in Helsinki (Helama *et al.* 2020). It appears that the signal of the growing season precipitation could be regarded as a common factor controlling tree growth in various site conditions around the Gulf of Finland and the northern Baltic Sea continental margin proper, but its strength may vary, as further demonstrated for the sites examined in this study.

Correlations of tree-ring chronologies with other climatic variables were found to be more variable. It was determined that at the INTM site, the tree-ring chronology was linked positively with the late-winter (March) temperature. Similar climatic signals were previously found in Scots pine tree-ring data with positive correlations with March temperatures in Estonia (Läänelaid *et al.* 2009), with February–March temperatures in Novgorod (NW Russia) (Helama *et al.* 2017), and with February, March, and April temperatures in Lithuania (Juknys *et al.* 2002) and Poland (Koprowski *et al.* 2012).

Generally, these findings indicate a common climatic signal in tree-ring chronologies around the Baltic Sea region (Läänelaid *et al.* 2012), which is also represented by the tree-ring variability in the southwest Finland. At the MNLD site, the pine growth showed a negative correlation with the late-autumn precipitation (previous October to the growth year). Previously, the Scots pine growth was negatively associated with snow depth at the beginning of dormancy (November) in the regional tree-ring chronology representing sites around the southern part of Finland (Helama *et al.* 2013). The seasonal timing of the late-autumn (October) precipitation signal at the sites of this study appears to predate, however, the accumulation of snow covers in the study region (based on the estimates of Aalto et al. (2016) for the 2016–2020 period), which suggests that the mechanisms controlling the responses are dissimilar. Collectively, these results demonstrate the relative importance of climatic conditions outside the growing season for Scots pine in the study region.

Importantly, the findings of this study offer implications for palaeoclimate research. In the City of Turku, archaeological excavations have resulted in numerous finds of wooden artefacts, including construction timber. A particularly rich source of such materials for tree-ring studies is likely to originate from urban medieval deposits (e.g., Zetterberg 2003; Seppänen 2012). Dead wood materials provide sequences of tree rings for a long local/regional chronology to be used for further dating purposes. The resulting tree-ring data provide an annually resolved, well-dated palaeoclimatic resource to be used for estimations and reconstructions of past climate variability in the same region. Calibration and verification statistics shown here (Table 1) suggest a potential for new hydroclimatic reconstructions sensitive to late spring-summer precipitation surpluses and droughts. This would corroborate previous studies where Scots pine tree rings were used as proxy data for reconstructing the growing season precipitation variability elsewhere at the sites around the Gulf of Finland and the northern Baltic Sea region (Helama, Lindholm 2003; Linderholm, Molin 2005; Helama *et al.* 2009b; Jönsson, Nilsson 2009; Seftigen *et al.* 2013, 2015, 2017). Such reconstructions can potentially provide a late Holocene context for the recent and forecasted precipitation trends in southwest Finland (Ylhäisi *et al.* 2010).

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