

## AN 854-YEAR TREE-RING CHRONOLOGY OF SCOTS PINE FOR SOUTH-WEST FINLAND

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### Abstract

A near-millennial tree-ring chronology (AD 1147–2000) is presented for south-west Finland and analyzed using dendroclimatic methods. This is a composite chronology comprising samples both from standing pine trees (*Pinus sylvestris* L.) and subfossil trunks as recovered from the lake sediments, with a total sample size of 189 tree-ring sample series. The series were dendrochronologically cross-dated to exact calendar years to portray variability in tree-ring widths on inter-annual and longer scales. Although the studied chronology correlates statistically significantly with other long tree-ring width chronologies from Finland over their common period (AD 1520–1993), the south-west chronology did not exhibit similarly strong mid-summer temperature or spring/early-summer precipitation signals in comparison to published chronologies. On the other hand, the south-west chronology showed highest correlations to the North Atlantic Oscillation indices in winter/spring months, this association following a dendroclimatic feature common to pine chronologies over the region and adjacent areas. Paleoclimatic comparison showed that tree-rings had varied similarly to central European spring temperatures. It is postulated that the collected and dated tree-ring material could be studied for wood surface reflectance (blue channel light intensity) and stable isotopes, which both have recently shown to correlate notably well with summer temperatures.

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**Key words:** dendrochronology, North Atlantic Oscillation, paleoclimate, *Pinus sylvestris*, subfossil wood.

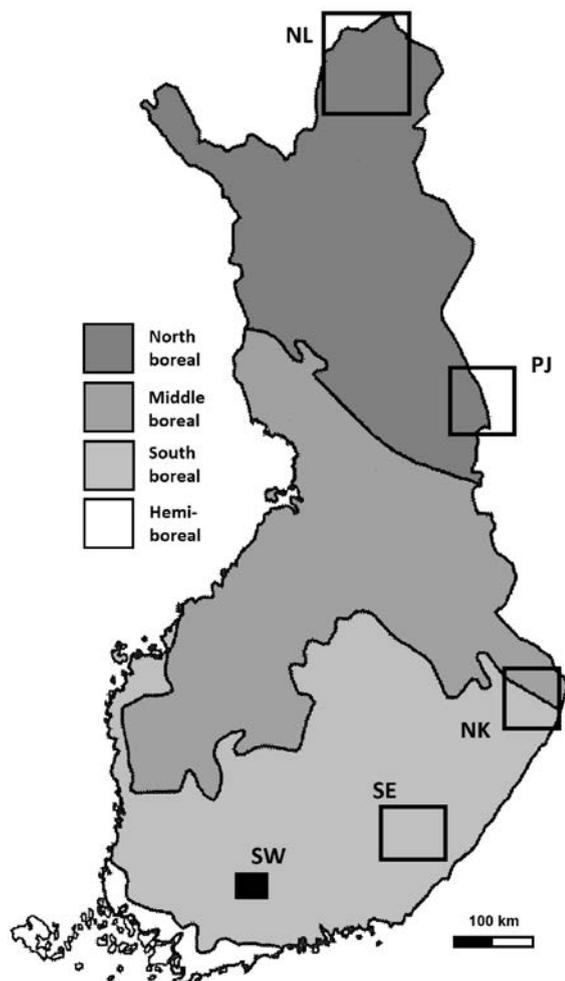
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### INTRODUCTION

Tree rings provide late Quaternary paleoenvironmental records (Bradley, 1999; Walker, 2005). Millennia-long tree-ring chronologies have recently been constructed in Fennoscandia where their development is an ongoing activity (Linderholm *et al.*, 2010). These records consist of composite chronologies where the living-tree series are combined with tree-ring series from subfossil trunks of pine, usually preserved in subaerial conditions or sedimentary archives of small lakes or bogs (Bartholin and Karlén, 1983; Eronen *et al.*, 1999, 2002; Grudd *et al.*, 2000, 2002; Linderholm and Gunnarson, 2005). Majority of these chronologies originate from regions near the timberline. Construction of long chronologies is however possible also for more southern regions, either similarly using naturally preserved wood or by utilizing samples from historical buildings (Bartholin, 1987; Läänelaid and Eckstein, 2003; Koprowski *et al.*, 2012). The value of these records for paleoenvironmental studies has been proven as the tree-ring chronologies have provided in-

formation of past climate variability from inter-annual to millennial scales and for various spatial domains (Grudd *et al.*, 2002; Helama *et al.*, 2002, 2009a, 2009b, 2009c, 2010; Helama and Lindholm, 2003; Linderholm and Gunnarson, 2005; Gouirand *et al.*, 2008).

Here we demonstrate the development and characteristics of a near-millennial tree-ring chronology of Scots pine for a site in south boreal forest zone in south-west Finland. This is a region where no such long tree-ring record has been available before the development of this chronology and where no subfossil wood recovered from lake sediments have previously been used for construction of tree-ring chronologies. Previously, the most recent part of the chronology has been used for dendroclimatic research and compared with instrumentally observed climate records from the same region (Holopainen *et al.*, 2006). Similarly, the chronology was compared with large-scale climate indices (North Atlantic Oscillation NAO; Hurrell, 1995; Hurrell *et al.*, 2001). These studies found out the sensitivity of the chronology to conditions in winter (Helama and Timonen, 2004) and spring



**Fig. 1.** Location of the study site in south-west Finland (SW) and regions from which the other long chronologies originate in northern Lapland (NL), Pääjärvi (PJ), North Karelia (NK) and south-east Finland (SE).

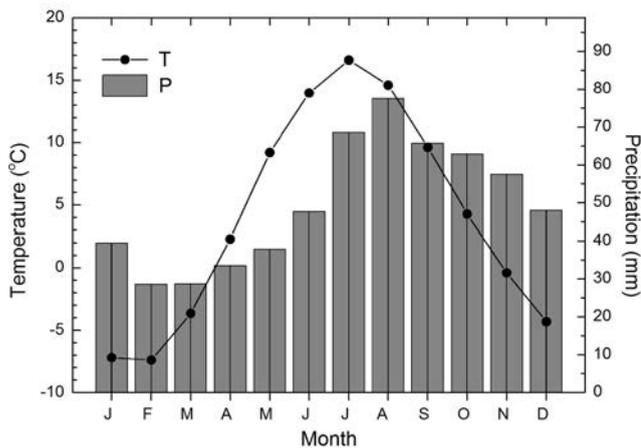
(Holopainen *et al.*, 2006) climate. However, the correlation to spring temperature variability appeared temporally unstable (Holopainen *et al.*, 2006). Moreover, the chronology was correlated with several other tree-ring chronologies of Scots pine from adjacent areas to reveal that their spatial correlation likely reflects the past fluctuations in the NAO (Lääne-laid *et al.*, 2012).

Our objective here is to detail the chronology construction by demonstrating its temporal characteristics in sample size and chronology confidence, in addition to the tree-ring width variations. Moreover, the dendroclimatic correlations are derived using local climate data and the NAO indices. This procedure follows our previous analyses of late Holocene tree-ring chronologies from Finland (Helama *et al.*, 2005) thus enabling comparisons of these chronologies and characterizing the properties of the south-west Finnish chronology as paleoenvironmental record. Additional comparison is made for the subfossil part of the chronology by comparing the tree-ring variations in the study region with the temperature variability as reconstructed for central Europe using documentary data (Pfister and Brázdil, 1999) over the 16th century.

## MATERIAL AND METHODS

Our tree-ring material originates from Lake Kaitajärvi and Lake Vähä-Melkutinjärvi (60°40' N, 23°35' E) situated in south-west Finland (Fig. 1). The site is located in the south boreal zone (Ahti *et al.*, 1968). This tree-ring dataset of Scots pine (*Pinus sylvestris* L.) comprise 189 series. Living tree samples were cored at the m trees growing at the shore using increment borer at breast height. Subfossil samples were recovered from lake sediments. Disks were cut by saw after lifting the trunks to the surface and sampled trunks were returned into the lake. Series of tree-ring widths were produced by measuring the ring-widths under a light-microscope to the nearest 0.01 mm. The sample series were dated using tree-ring cross-dating, a routine of dendrochronology, where the temporal variability of conspicuously wide and narrow rings are examined and each ring can be dated to exact calendar years (Fritts, 1976). Cross-dating was obtained using numerical procedures (Holmes, 1983; Van Deusen, 1990), in addition to visual comparison of the plotted measurement series on the computer screen. The dating process initiates from the cross-dating of series from living trees. The subfossil series are cross-dated against each other and the subfossil chronology is cross-dated against the obtained chronology of living trees. The final chronology comprises 47 sample series from living pines and 142 subfossil series. Mean length of the series was 143 years. The chronology covered the period AD 1147–2000.

Following previous tree-ring studies in adjacent areas (Helama *et al.*, 2005, 2013), the double-detrending of the tree-ring series was carried out. To do so, individual tree-ring series were transformed into indexed series in the process called tree-ring standardization (Fritts, 1976; Cook, 1985; Helama *et al.*, 2004). This was done to remove the age-size related trend in radial growth using the modified negative exponential curve, linear regression line or line through the series mean (Fritts *et al.*, 1969). Indices were derived from the modeled curve by division. Second, a spline function (Cook and Peters, 1981) was fitted to the series of these indices and a new series of tree-ring indices were extracted from this curve as ratios. The rigidity of the spline was determined to be two-thirds of the length of each individual time series (50 % frequency response cut-off). Third, the second set of indices was pre-whitened using Box and Jenkins (1970) methods of autoregressive and moving average time series modeling (Cook, 1985). The rationale using this three-step process lies as follows. The first detrending is expected to remove the long-term growth trend from the tree-ring measurement series and to stabilize their variance. The second detrending is expected to remove growth variation related to disturbance caused by forest dynamics with additional variance stabilization (Fritts, 1976; Cook *et al.*, 1990a; Helama *et al.*, 2004). Pre-whitening transforms autocorrelated series into serially independent observations (Cook, 1985; Monserud, 1986). Expressed population signal (EPS) was used as indication of chronology reliability. The EPS provides an expression of common variability among the available tree-ring series through time. The pre-determined limit of  $\text{EPS} > 0.85$  can be used as a reasonable albeit objective value for an acceptable level of chronology confidence (Wigley *et al.*, 1984).



**Fig. 2.** Ombrothermic diagram of long-term mean monthly temperatures (T) and monthly precipitation sums (P) in the locality over the dendroclimatic study period (1910–1993).

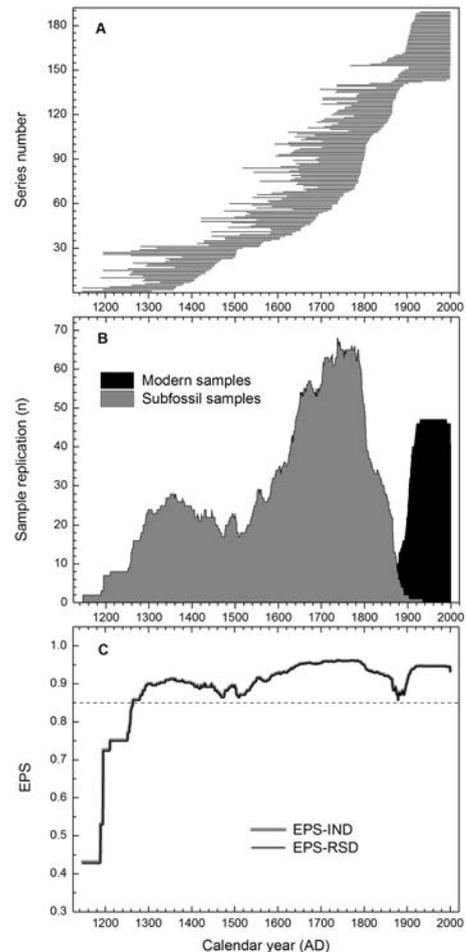
Tree-ring chronologies were produced by averaging the annual values of indices using a bi-weight robust mean (Cook, 1985; Cook *et al.*, 1990b). In order to adjust the chronology variance for sample size, each annual value was scaled by an effective number of independent samples available in each year as demonstrated by Osborn *et al.* (1997). The long-term and period variations in the chronology were illustrated by applying a smoothing spline function (Cook and Peters, 1981) to the annual chronology values. Hereafter, the pre-whitened indices were used in the analyses, if not otherwise mentioned.

Local climatic data was adopted as mean monthly temperatures and precipitation sums as estimated (Fig. 2) from the climate records made by the Finnish Meteorological Institute (Ojansuu and Henttonen, 1983). Moreover, the monthly indices of the North Atlantic Oscillation (NAO; Hurrell, 1995) were used for comparisons. The variations described by the NAO indices are characterized by the oscillation of atmospheric masses producing large-scale changes in the mean wind speed and direction over the North Atlantic, where the positive (negative) NAO phases commonly occur with strengthened (attenuated) westerlies and thus milder and moister (cooler and drier) winters and springtime conditions on local scale (Uvo and Berndtsson, 2002; Helama and Holopainen, 2012). Pearson correlation coefficients were computed between these climatic records and the tree-ring chronology. Correlations were calculated over the period 1909–1993. The particular period was common to our previous analyses (Helama *et al.*, 2005) thus making the dendroclimatic coefficients between that and this study comparable with each other.

## RESULTS

### Tree-ring properties

On average, the modern and subfossil pine series contained 109 and 154 rings with mean radii (sum of measured ARWs) of 164 and 150 mm, respectively, these values translating into absolute growth rates of 1.50 and 0.97 mm/year. These figures indicate that the cored pines had grown faster



**Fig. 3.** Tree-ring chronology for south-west Finland. Each sample of the chronology, represented by a horizontal bar, is shown in its position corresponding to the dendrochronological cross-dating (a). Replication of the samples as a function of time (b). The expressed population signal (EPS) and its temporal variations relative to the pre-determined level of 0.85 (horizontal dashed line) (c).

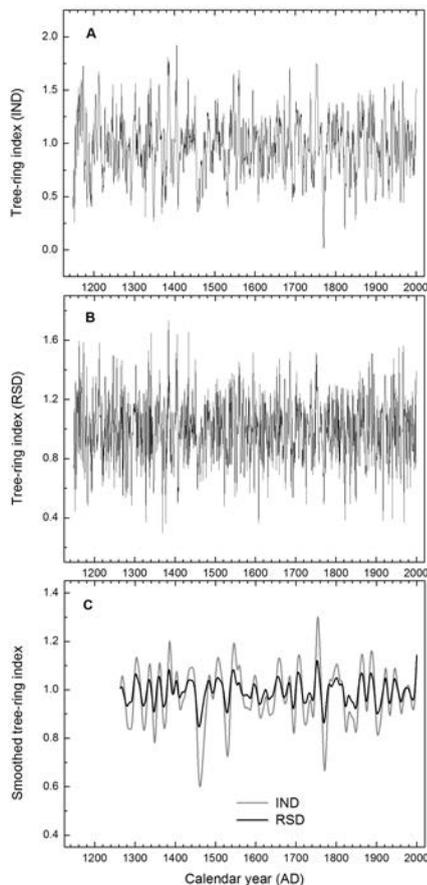
than the ancient pines recovered from the lake sediment. The oldest living pine was more than 233 years old. Its first ring at breast height had grown in 1768. In comparison, the biologically oldest subfossil pine contained 309 rings.

### Chronology confidence

Sample size fluctuates through time with highest number of replication during the 18th century (Fig. 3). Periods of low sample replication occur during the last half of the 19th century and before 17th century. Correlation among tree-ring series averaged 0.275 and 0.272, respectively, as calculated from detrended and further pre-whitened indices. Using these values and the EPS-statistic, the chronologies build using detrended and further pre-whitened indices showed the EPS-statistic over the pre-determined level of 0.85 continuously since 1264.

### Tree-ring fluctuations

Chronologies illustrated tree-ring growth variations on inter-annual to longer scales (Fig. 4). The most anomalous

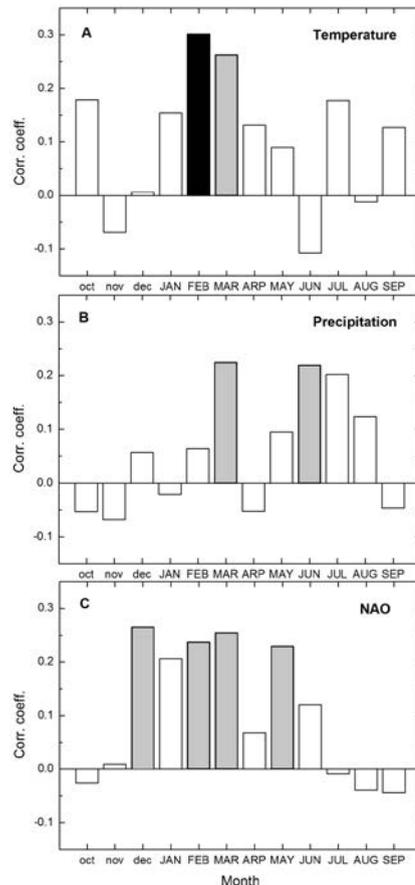


**Fig. 4.** Tree-ring chronologies based on detrended (a) and further pre-whitened (b) indices. Long-term variations of the chronologies are highlighted using their smoothed versions (c). The smoothed chronologies are shown since their EPS-statistic exceed the 0.85 level (Fig. 3c).

positive indices were found in 1384, 1434, 1341 and 1406. No similarly positive indices occurred in the course of the 20th century. The eye-catchingly anomalous negative growth indices were found in 1328, 1369, 1377, 1608 and 1823. During the 20th century, the years 1917, 1940 and 1969 underwent similarly negative indices. Notable periods of ameliorated growth occurred in the 1380s, 1540s and 1750s. Corresponding period of deteriorated growth were evident in the 1460s, 1530s, 1770s. This shows that the period from 1530s to 1540s experienced a marked change in the growth from low to high index values.

### Dendroclimatic correlations

Tree-rings were found to correlate statistically significantly with several monthly climatic variables as follows. Positive correlations were found for temperatures in February and March (Fig. 5a). Calculating the correlation between the tree-ring chronology and the February–March temperature series showed a correlation coefficient of 0.338 ( $p < 0.01$ ). This indicates that the tree-ring growth was benefitted from mild winter conditions prior to the actual start of the growing season. Moreover, the tree-ring chronology correlated positively with precipitation in March and June (Fig. 5b). Since the



**Fig. 5.** Dendroclimatic correlations computed between the monthly climate variables and tree-rings (AD 1910–1993). Columns show the correlation coefficients for temperature (a) and precipitation (b) variables as well as the indices of the North Atlantic Oscillation (NAO) (c) of the previous (small letters) and concurrent year (capital letters). Statistically significant relationships are indicated as black (0.01 level) and gray (0.05 level) histograms.

local March mean temperature typically remains below zero (Fig. 2), the correlativity to March precipitation likely demonstrates the positive effects from increased snowfall on these pines.

### NAO-correlations

Statistically significant correlations to the NAO indices were found for winter and spring months preceding the growing season in December, February, March and May (Fig. 5c). Highest correlation between the NAO indices and tree-rings was found for a multi-monthly season (December through May) combining the winter and spring months. This correlation showed a coefficient of 0.483 ( $p < 0.01$ ). This multi-monthly NAO index recognized firm linkages with the local temperature and precipitation records with statistically significant correlation coefficients of 0.628 ( $p < 0.01$ ) and 0.295 ( $p < 0.01$ ), respectively. These associations demonstrate the NAO-driven effects on the local winter (December through May) climate variability where the westerly winds, as indicated by the positive NAO index, arrive into the region with warmer and more humid air masses.

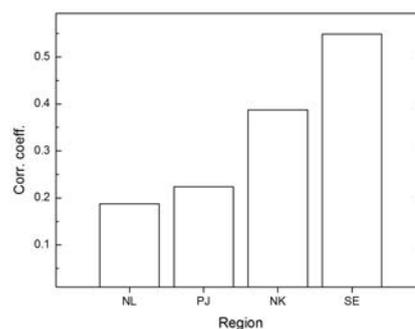
## DISCUSSION

We have demonstrated the main characteristics of the near-millennial tree-ring chronology from south-west Finland. Comparison between this chronology with other long Finnish tree-ring chronologies of Scots pine show that the tree-ring variations of the studied chronology correlate best with the chronology from south-east Finland (Fig. 6), that is, with its geographically closest record. Moreover, the correlations decrease systematically as the distance between the chronologies increases. This decline occurs in accord with the previous views on spatial tree-ring correlativity in Fennoscandia (Schweingruber, 1988; Helama *et al.*, 2005) and likely results, in part, from decreasing similarity between the climate variability with increasing distance. Even a stronger factor behind the decline is likely to originate from dissimilarity of tree-ring growth response to climate in different ecological positions from southern boreal forests to the northern timberline. Comparison of these dendroclimatic relationships is presented below.

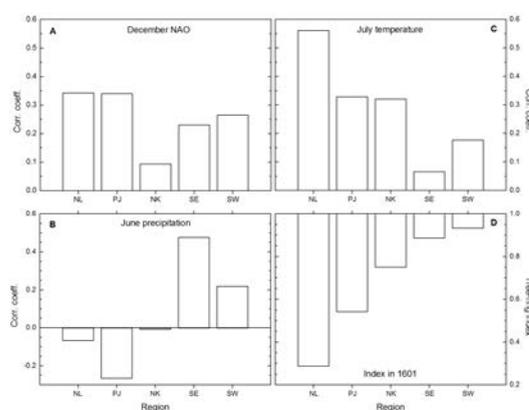
### Cold season and hydroclimate signals

Our results confirmed the previous findings that these tree-rings correlate notably with the climatic variables in winter and spring seasons (Helama and Timonen, 2004; Holopainen *et al.*, 2006) and that the tree-ring variability follows the positive and negative NAO phases at least over the instrumental period (Helama and Timonen, 2004; Läänelaid *et al.*, 2012). The NAO is an atmospheric oscillation of synoptic scale over the North Atlantic sector where the westerlies bring warmer and moister air-masses onto study region (Uvo and Berndtsson, 2002; Helama and Holopainen, 2012). This condition is demonstrated by the positive NAO index. In its opposite phase, the westerlies are attenuated with predominance of cooler and drier conditions over the north-west Europe (Hurrell, 1995; Hurrell *et al.*, 2001). In this study, the atmospheric phenomenon was indicated by markedly positive correlations between the NAO index and the local temperature and precipitation variability during the winter and spring seasons. Comparison of the NAO-correlations in south-west Finland with previously established NAO-correlations (Helama *et al.*, 2005) shows that the winter (December) NAO index correlates with pine growth over extended areas (Fig. 7a). Similar correlativity of Scots pine tree-rings to winter NAO index has been observed over multiple sites in Finland, Estonia, Gotland, and north-west Russia (Lindholm *et al.*, 2001). Moreover, it has been found that the prolonged periods of positive NAO phase come with increased correlation between the tree-ring chronologies over the same region through the past millennia (Helama *et al.*, 2005; Läänelaid *et al.*, 2012).

It is evident that the tree-ring growth is generally benefited from the mild and moist winter/spring conditions through Finland and adjacent areas as in fact evidenced by statistically significant correlations to temperature (February through March; Fig. 5a) and precipitation (March; Fig. 5b) variables of cold season. The most obvious paleoenvironmental change as indicated by the chronology occurred as the mid-1500s event, when the anomalously low indices in the

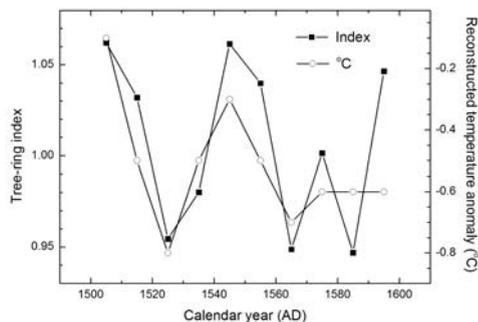


**Fig. 6.** Correlations between the tree-ring chronology of this study and the other long Finnish tree-ring chronologies (Helama *et al.*, 2005) originating from northern Lapland (NL), Pääjärvi region (PJ), North Karelia (NK), and south-east Finland (SE) (see also Fig. 1). Correlations were calculated over the common period (AD 1520–1993). All correlations are statistically significant ( $p < 0.01$ ).



**Fig. 7.** Comparison of the Finnish millennial tree-ring chronologies using their dendroclimatic correlations (Helama *et al.*, 2005) to North Atlantic Oscillation (NAO) index in December preceding the growing season (a), precipitation in June (b), temperature in July (c), and their tree-ring indices in AD 1601 (d). Chronologies originate from northern Lapland (NL), Pääjärvi region (PJ), North Karelia (NK), south-east Finland (SE) and this study (SW) (see also Fig. 1).

1530s were followed by the high index values in the 1540s. Of note, Pfister and Brázdil (1999) detailed the temperature and precipitation variation in central Europe using documentary data. They further reconstructed climate variability over the 16th century using decadal estimates of past temperature and precipitation. We compared their reconstructions to decadal averaged tree-ring indices from south-west Finland and obtained highest correlation with coefficient of 0.751 ( $p < 0.05$ ) reasonably for a spring temperature association (Fig. 8). Moreover, the temperature reconstruction (Pfister and Brázdil, 1999) exhibited a positive change towards the 1540s, comparable to indications by the studied tree-ring chronology. These findings implied a rather similar spring temperature changes in central and northern Europe, at least on decadal scale, during the 16th century. In a previous analysis, the SW Finnish tree-rings were seen to correlate positively with reconstructed and instrumentally recorded spring temperature variations in the same region since 1750s (Holopainen *et al.* 2006). The strength of the correlativity was however temporally unstable. Similarly, the correspon-



**Fig. 8.** Decadal comparison of the south-west Finnish tree-ring index and the estimated central European temperature variations as anomalies from the reference period 1901–1960 (Pfister and Brázdil, 1999).

dence between the two records here (Fig. 8) is somewhat muted during the last decades of the 16th century.

Previously, the millennial tree-ring chronology of Scots pine from south-east Finland was used as a proxy record for reconstructing the paleoclimatic variations in past spring–summer (May through June) precipitation (Helama and Lindholm, 2003; Helama *et al.*, 2009b). Similarly, the tree-rings correlated statistically significantly with June precipitation in south-western Finland (Fig. 5b). However, the dendroclimatic signal of summer precipitation was notably lower in south-west Finland, in comparison to the strength of this signal in tree-ring growth in south-east Finland (Fig. 7b). Interestingly, this dendroclimatic relationships was found as markedly positive only for the sites in south boreal forests, in south-west and south-east Finland, in comparison to the more northern sites in Finland where the correlation appeared negative (Fig. 7b).

### Summer temperature signals

In Fennoscandia, the longest tree-ring chronologies have been commonly built for northern timberline regions where the utilization of subarctic wood (Sirén, 1961; Bartholin and Karlén, 1983; Bartholin, 1987) as well as the recovery of subfossil pine trunks as preserved within lake sediments (i.e., megafossils) started several decades ago (Eronen, 1979). These chronologies have oftentimes been used as proxy records for reconstructing the paleoclimatic temperature variations through past millennia (Grudd *et al.*, 2002; Helama *et al.*, 2002, 2009a, 2009c, 2010; Linderholm and Gunnarson, 2005; Gouirand *et al.*, 2008). Naturally, their paleoclimatic value depends on their strong dendroclimatic signal of summer temperatures. Also the south-west chronology relates positively with mid-summer (July) temperatures (Fig. 5a) but the strength of this correlation is dwarfed by the high association between mid-summer temperatures in the tree-ring chronologies from more northern areas (Fig. 7c). Yet another suitable way for studying this paleoclimatic signal in Finnish tree-ring chronologies is the comparison of tree-ring indices of the chronologies in AD 1601 (Helama *et al.*, 2005; Helama *et al.*, 2009a). This year is known as one of the most obvious signature years in the northern tree-ring chronologies (Briffa *et al.*, 1998) following the summertime

cooling over the Northern Hemisphere due to the eruption of Huaynaputina volcano (Peru) that had occurred in the previous year (de Silva and Zielinski, 1998). As a result of this cooling, the timberline tree-rings demonstrated most severe reduction in their growth, as indicated by their very low tree-ring index, in AD 1601 (Fig. 7d). A similar, albeit attenuated, growth reaction was observed in more southern chronologies, with a pattern of gradually weaker response towards the south, with the highest tree-ring index in AD 1601 in the south-west Finnish chronology (Fig. 7d). It is obvious that the studied chronology possesses a negligible summer temperature signal in its tree-rings, in comparison to chronologies from more northern areas.

Although the summer temperature signal in the south-west Finnish chronology of tree-ring widths appeared meaningless, the collected tree-ring material could provide an improved paleoclimatic temperature proxy archive for analyses of the surface reflectance of the latewood portion of each annual ring to determine the minimum blue channel light intensity (BI). Previous studies have shown that the BI provides a highly skilled surrogate for latewood density of high-latitude pine tree-rings (McCarroll *et al.*, 2002; Campbell *et al.*, 2007; Wilson *et al.*, 2011). The BI was recently (Helama *et al.*, 2013) shown to provide a useful proxy for past temperature variations also south of the timberline, as the BI chronology of living pines explaining more than 40 percent of the summer temperature variance in North Karelia (denoted as NK in Fig. 1) in eastern Finland. Alternatively, the collected tree-ring material could be used as material for dendro-isotopic analyses. Stable carbon isotopes ( $\delta^{13}\text{C}$ ) as extracted from Scots pine tree-rings have previously shown to provide a reasonable proxy of temperatures in North Karelia where the  $\delta^{13}\text{C}$  chronology explained 30–40 percent of the summer temperature variance (Hilasvuori *et al.*, 2009). Analyzing these properties from Scots pine tree-rings in south-west Finland for BI and  $\delta^{13}\text{C}$  chronologies over the periods of instrumental climate observations (Holopainen, 2006) will detail their exact paleoclimatic value. Another interesting opportunity would use both the BI and  $\delta^{13}\text{C}$  data as multiple proxies for common temperature signal, as an increased range of indicators is likely to result in more robust paleoclimate reconstruction.

### CONCLUSIONS

Tree-ring chronology from south-west Finland provides an interesting possibility to study the paleoenvironmental variations over the past eight centuries. Although the dendroclimatic correlations between this chronology and local climate variables did not indicate straightforward opportunities for tree-ring based temperature or precipitation reconstructions, the chronology showed its potential for recording the NAO signals of winter and spring seasons. Moreover, the markedly high correlation between the tree-ring chronology and reconstructed central European temperatures during the 16th century was demonstrated. This comparison showed that the past variations in the tree-ring width were synchronous with large-scale temperature fluctuations also during the pre-instrumental period. As a future prospect, the tree-ring dated material may be used for more elaborated proxies

of summer temperature via production of wood property and/or dendro-isotopic chronologies.

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