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MULTICENTENNIAL RING-WIDTH CHRONOLOGIES OF SCOTS PINE ALONG A NORTH–SOUTH GRADIENT ACROSS FINLAND

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ABSTRACT

Four regional Scots pine ring-width chronologies at the northern forest-limit, and in the northern, middle and southern boreal forest belts in Finland cover the last fourteen centuries. Tree-ring statistics and response functions were examined, and tree-ring width variation was also compared to North Atlantic Oscillation (NAO) and volcanic forcing. The tree-ring statistics show evidence of an ecogeographical gradient along a north–south transect. The three northernmost regional chronologies share a positive response to mid-summer temperature, and all four chronologies show positive and significant correlation to early-summer precipitation. Moreover, a positive and significant relationship to winter NAO was detected in three out of four regional chronologies. NAO also drives the common (inter-regional) growth variability. Years of known cool summers caused by volcanic forcing exhibit exceptionally narrow tree rings in the three northernmost regional chronologies.

Keywords: Dendroclimatology, Scots pine, Finland, subfossil, North Atlantic Oscillation, volcanic forcing.

INTRODUCTION

The study of Scots pine tree rings has a long tradition in Finland. Recent dendroclimatological advances have yielded century and millennium-

length regional ring-width chronologies for northern, central and southern Finland. These chronologies result from a long program of sample collection that has produced large numbers of cross-dated tree-ring series from natural and historical archives. Dendrochronologically well-developed

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regions form a transect across the country. Some of these chronologies are available in the ITRDB (<http://www.ngdc.noaa.gov/paleo/treering.html>). Recently, chronology construction in northern Finland culminated in a seven and one-half millennium-long continuous Scots pine ring-width chronology (Eronen *et al.* 2002).

The present work consists of two parts. Firstly, each regional chronology is described by means of its statistical properties and response functions. Results are shown in the context of a north–south transect that reveals a possible ecogeographical tree-ring gradient from the northern forest-limit region to the southern boreal forest interior. Secondly, radial growth variations are compared to known volcanic events and North Atlantic atmospheric circulation patterns over the last five centuries. This comparison is aimed at producing information on past relationships between environmental conditions and tree growth in Finland on interannual-to-interdecadal timescales. In relation to previous work (*e.g.* Lindholm *et al.* 2000), our analysis includes greatly strengthened regional mean time series, a larger number of statistics (to determine the ecogeographical position of each regional dataset along the transect), as well as a comparison of tree rings with internal and external climate forcings. Results derived here can be used as a basis for ecogeographical tree-ring studies on a broader spatial scale, and they contribute to paleoecology as the known volcanic events provide a high-resolution tool for assessing the past response of these regional chronologies to the growing seasons of extreme climatic conditions. The analysis also illuminates the relationship of large-scale atmospheric circulation to tree-ring variability and its spatiotemporal evolution over past centuries.

MATERIAL AND METHODS

North–South Transect of Tree-Ring Chronologies

Four regional Scots pine (*Pinus sylvestris* L.) tree-ring width chronologies are located along a north–south transect of 900 km (560 miles). The material was collected from the forest-limit in northern Finnish Lapland (415 trees), Pääjärvi (Pyaozero) (94 trees), North Karelia (156 trees)

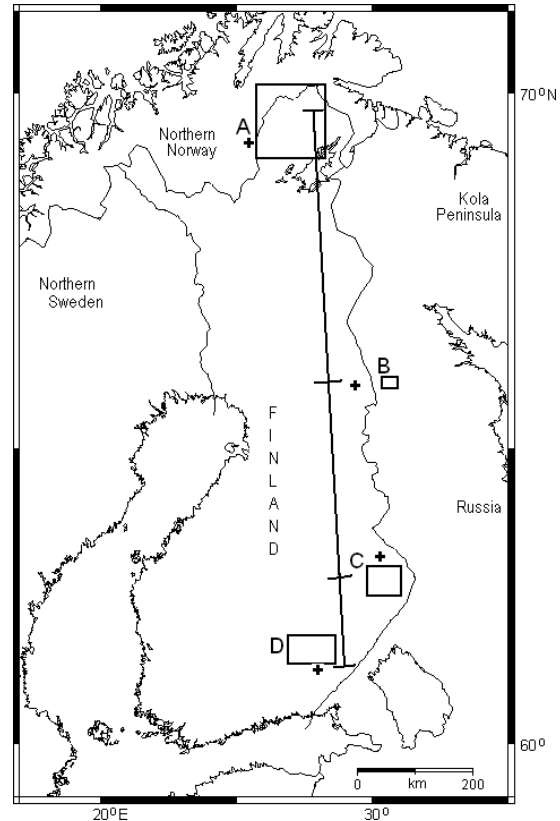


Figure 1. Geographical distribution of the regional chronologies A, B, C and D along the north–south transect. Crosses (+) represent the meteorological stations.

and Lake Saimaa basin district in southeast Finland (563 trees) with abbreviations used hereafter from north to south as A, B, C and D (Figure 1), respectively. Cores from living trees in naturally grown sites, from dead standing trees and buildings were extracted with an increment borer. Samples were also collected from tree trunks in the bottom sediment of small lakes. Disks were cut after lifting the trunks to the surface, after which the trunks were returned into the lake (Eronen *et al.* 2002). The ring widths were measured to the nearest one-hundredth of a millimeter. Tree-ring series of each tree were estimated by an arithmetic mean of measurements along different radii of each tree. Series of ring widths were then carefully crossdated using several numerical procedures (Aniol 1983; Holmes 1983; Holmes *et al.* 1986; van Deusen 1990) in addition to visual comparison of the series on a light table.

The northernmost sampling sites (Region A) are situated along the forest-limit zone. They represent sites at the worldwide distribution limit of the species (Mirov 1967). Samples were extracted from living trees, dead standing trees and from subfossil wood preserved in the sediment of small lakes. This dataset is a subsample of the multi-millennial ring-width chronology of Eronen *et al.* (2002). The second set of samples (Region B), including dead and living trees, comes from the border of the north and middle boreal forest belts (*sensu* Ahti *et al.* 1968). It was presented earlier by Lindholm (1996). The third set of samples (Region C) comes from the border of the middle and south boreal forest belts, whereas the southernmost samples (Region D) clearly originate from the southern boreal forest belt. An earlier version of the southernmost chronology was briefly discussed by Lindholm *et al.* (1998–1999); here the chronology is 200 years longer and in a more statistically reliable form, owing to the ongoing advances in dendrochronology in that part of the country. The latter two datasets (Region C and D) both contain samples from living trees, construction timber and preserved trunks in the sediment of small lakes and peat bogs.

Meteorological Time Series

Meteorological data come from four weather stations, each located in the vicinity of the dendrochronological study region (Figure 1). Station records (from north to south) of Karasjok, Kuusamo, Lieksa and Lappeenranta all contain instrumental measurements of monthly mean temperature and total monthly precipitation for the last 90 years. Annual mean temperatures at the stations are -2.0 , -0.4 , 1.9 and 3.6°C from north to south, respectively, and annual precipitation totals, are 343, 576, 597 and 632 millimeters from north to south, respectively. To estimate the relationship between tree-ring width and North Atlantic Oscillation (NAO), monthly indices derived by Hurrell (1995) were used.

Ring-Width Indices

Individual ring-width series were indexed using a two-step process of Holmes *et al.* (1986) called

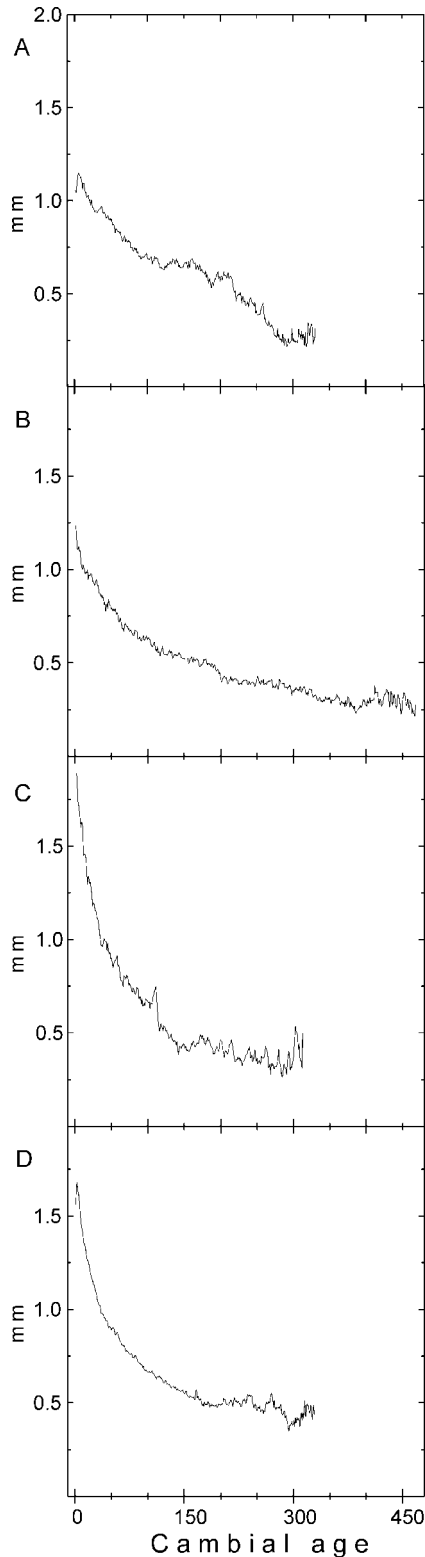
double-detrending. A negative exponential curve or a linear regression line with a negative slope or line through the series mean were fitted to the measurement series, and indices were derived from the curve by division. Using the formula of Fritts *et al.* (1969), a negative exponential curve can be modeled as:

$$y = ae^{-bx} + k, \quad a > 0, \quad b > 0, \quad [1]$$

where a determines the initial height of the curve, b controls its concavity and k is a constant representing the translation of the x -axis (tree cambial age). This function is mainly expected to capture the age-size related trend in radial growth. A spline function (Cook and Peters 1981) with a frequency response of two-thirds of the individual series length with 50 percent cutoff (Cook 1985) was fitted to the ratio-based indices of the first detrending, and final indices were derived from the curve by division. This fairly stiff spline function is expected to capture tree-ring variation related to disturbance caused by forest dynamics, *i.e.* non-climatic factors (Cook 1985). The indices were further prewhitened using Box and Jenkins (1970) methods of autoregressive and moving-average time-series modelling (*e.g.* Cook 1985; Monserud 1986). The order of the autoregressive-moving-average process was determined using Akaike (1974) information criteria. Prewhitening transforms autocorrelated series into a series of independent observations by extracting residuals from the modeled process.

Chronologies were produced averaging the annual values of indices by arithmetic mean. In order to adjust variance for sample size, each annual value was scaled by an effective number of independent samples available in each year (see Osborne *et al.* (1997) for details). Residual chronologies were used to examine variations in tree rings on an interannual basis, whereas standard chronologies (without prewhitening) were used to study variations of lower frequencies.

The Expressed Population Signal (EPS) statistic was used to measure chronology confidence. EPS is a function of mean intertree correlation (signal of common growth) and sample size (see Wigley *et al.* (1984)). For EPS, the level of 0.85 (Wigley *et al.* 1984) was used as a chronology confidence



limit. A quantitative analysis here is made only for those parts of the chronologies where EPS is greater than the predetermined level.

RESULTS AND DISCUSSION

Reliability of Chronologies

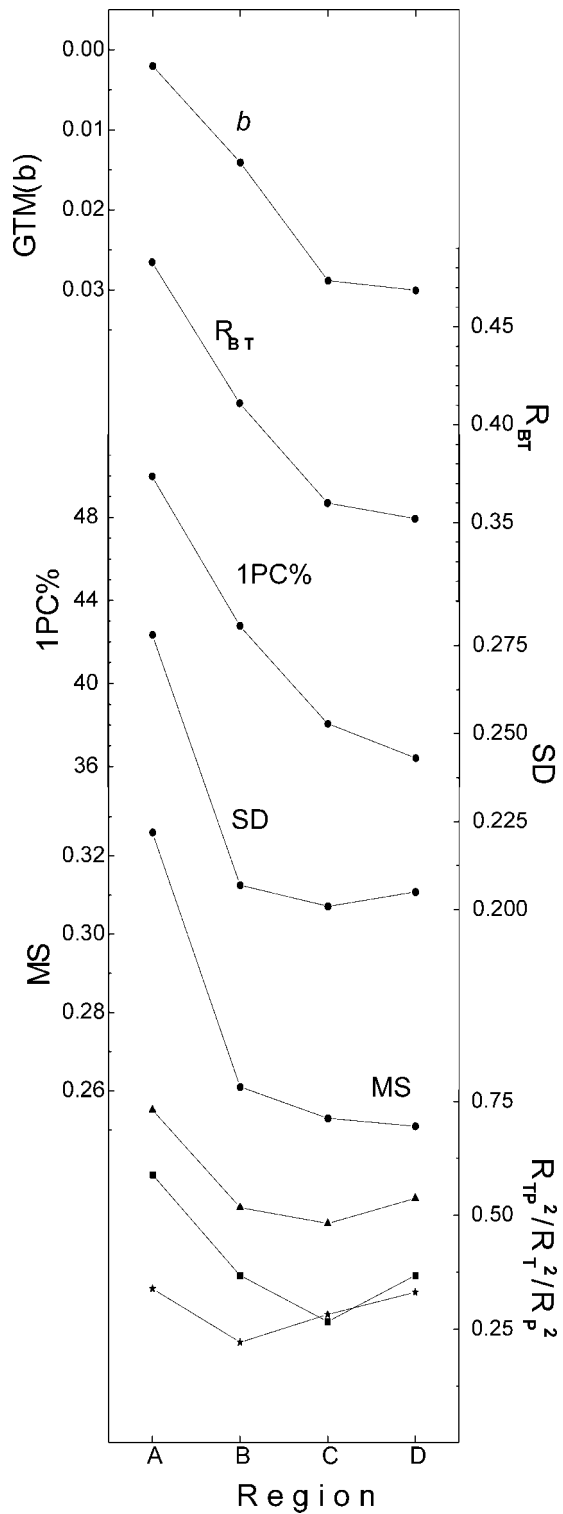
The chronology from Region A remains reliable (according to EPS-statistic) over its entire presented length. The chronology from Region B remains reliable continuously from A.D. 1520s to present and the chronology from Region C from the 1430s to present (and occasionally before that) (see Figure 5). The chronology from Region D is reliable from the 580s to present. The EPS-statistic determines the common period (1520–1993), which allows statistically reliable comparison between all four regional chronologies. Hereafter, comparisons between all four chronologies were made using this particular period if not indicated otherwise.

Tree-Ring Statistics

Individual series of ring widths, measured from pith to bark, are known to contain a trend, associated with age-size dependency in radial growth (Fritts *et al.* 1969; Cook 1987) (Figure 2). The juvenile stage of growth clearly exhibits a higher level in the two southernmost Regions (C and D) than in the two northern Regions A and B. In addition, narrowing of the ring widths after the juvenile stage of growth is stronger in the south compared to the north, revealed by a greater concavity of the average growth curves in Figure 2. This can be also observed in the change of the region-wide mean value of the constant b (Eqn. 1). That is, the mean value of b increases towards the south, indicating an increased concavity (narrowing of the ring widths) in age-size-related growth-trend models of individual measurement

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Figure 2. Average growth as a function of cambial age in the Regions A, B, C and D. After the juvenile growth maximum, radial growth experiences a more or less exponential decline, with greater concavity of the growth curves in the south than in the north (see also Figure 3).



series (see Eqn. 1). According to Mikola (1950), the juvenile maximum of Scots pine radial growth, as well as the concavity of the age-related ring-width curve, both show a general increase from north to south in natural forests in Finland. Mikola (1950) associated the change in the concavity of the growth trend with an increased growth competition in the same direction. We suggest that the change in the behavior of the age-size related growth trend models can be associated with an ecogeographical change through the transect.

In general, there is a gradual change in most of the computed region-wide ring-width statistics (Figure 3). The common growth signal (R_{BT} and 1PC% in Figure 3) decreases through the transect from north to south. The variability (mean sensitivity and standard deviation) shows a similar pattern of reduction southward with greatest change between Regions A and B. Increased interannual variability in pine ring widths from the southern parts of Finland to the northern forest-limit was noted already by Hustich (1948) and Mikola (1950). According to Fritts *et al.* (1965), the common growth signal and series variability are in general supposed to increase from forest interior to the distributional limit of the species. This is partly caused by wider inter-tree spacing (low tree density) near and at the forest-limit. Because of decreased impact of competition, tree growth is more strongly influenced by climate instead of disturbance occurring in the forest interior. This is expected to increase the common growth signal towards the north in the present study.

Chronology variance depends, at least to some degree, on the series intercorrelation within a region (Figure 3). That is, higher correlation between the individual tree-ring series can yield larg-

Figure 3. Variation in chronology statistics from region to region. Comparison includes the mean concavity of the age-related growth trend models by growth trend modelling (GTM; b in Eqn. 1), correlation between the trees (R_{BT}), variance explained by the first principal component (1PC%), standard deviation (SD) and mean sensitivity (MS). Variance explained by monthly variables of temperature (R_T^2) is shown as squares, variance explained by precipitation (R_P^2) as stars, and variance explained by both temperature and precipitation (R_{TP^2}) as triangles.

er variance in the chronology. Series intercorrelation within a region, on the other hand, increases with low growth disturbance and climatic severity. Harsh climate governs pine radial growth over a variety of sites with homogeneity at the northern forest-limit (Lindholm 1996). Moreover, standard deviation of annual mean temperatures is also higher in northern relative to southern Finland (Heino 1994), with an expected influence on tree-ring growth.

Climatic Forcing

The total chronology variance explained by temperature and/or precipitation variables (using linear regression) shows distinct differences from region to region (Figure 3). Climatic factors explain more variance in the ring widths in Region A than in any other regions. This difference is clearest for temperature alone. In the case of precipitation variables, pines from Region D exhibit nearly equal coefficients of determination (R^2) as pines from Region A.

Response functions (by Pearson correlation) using monthly climatic variables (1910–1993) exhibit parallel but also even reverse features among the four regions (Figure 4). It is noteworthy that there is a positive, significant impact of the concurrent July mean temperature on radial growth as a common factor for the three northernmost Regions (A, B and C). However, in the southernmost Region D, pines responded negatively to summer (June) temperatures, whereas total precipitation in May bears a positive, significant response to ring widths in all four regions. Early-summer (May–June) precipitation has a most prominent influence on growth in Region D, whereas precipitation in June and July has a negative, significant influence on the tree rings in Regions B and A, respectively. Considering the most significant climatic factors affecting the radial growth of pine, response functions from the north (Region A) and south (Region

D) are in line with works of Lindholm (1996) and Henttonen (1984), respectively. That is, the strong influence of mid-summer temperatures of the concurrent year on ring widths in the north gradually changes into a relatively more dominant influence of early-summer rainfall in the south (Lindholm *et al.* 2000).

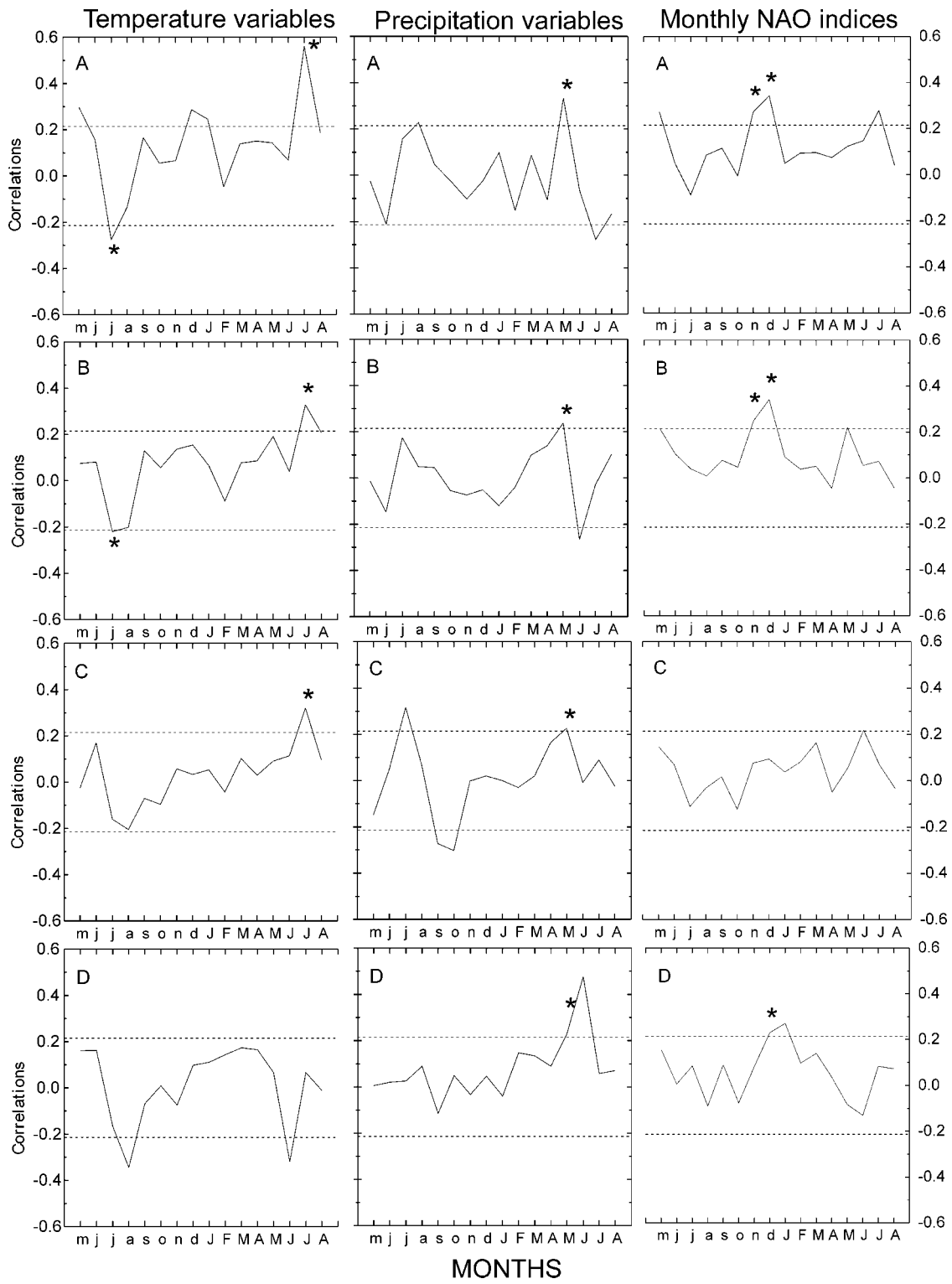
With regard to NAO, there is a gradual shift from late-fall/early-winter to enhanced early-winter impact from north to south (Figure 4), *i.e.* from Region A to B, and from B to D. Notably, no significant and negative relationship was found in any of the four chronologies. Relationships between winter-NAO and Scots pine growth in different parts of Finland have been reported previously by D'Arrigo *et al.* (1993), Cook *et al.* (1998), Lindholm *et al.* (2001) and Macias *et al.* (2004).

Correlations Between Regional Chronologies

In general, correlations between regional chronologies decrease with increased distance between regions (Figure 5). Correlations between the high-frequency components of ring-width variation decrease more rapidly with increasing distance than the correlations between the low-frequency components of the same data sets. That is, after the long-term variation has been extracted from total variation by Gaussian filters (Figure 5), correlations between these 'low-pass' filtered chronologies are higher with increased distance than correlations between the same chronologies containing more short-term variation (Figure 5). Also, when the chronology of Region D is compared with other regional chronologies, the correlations between the 'low-pass' filtered chronologies always exhibit the highest coefficients. This could, at least partly, result from a greater level of spatial correlation of (spring) rainfall (see response functions) on its low-frequency band (interdecadal) in relation to the high-frequency band (interannual). Alternatively, this can be caused by more intense

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Figure 4. Pine radial growth response (correlation) to monthly mean temperatures, precipitation sums and North Atlantic Oscillation (NAO) indices of previous (with a lower-case letter) and concurrent year of growth (with an uppercase). Horizontal dashed line represents the level of significance ($p < 0.05$) for Pearson correlations, asterisks (*) mark those monthly variables bearing (significant) impact on radial growth in at least two regions.



variation in (winter) NAO at decadal and bi-decadal time-scales (see Figure 4). Variations of NAO on these same time-scales were indeed reported by Rogers (1984) and Cook *et al.* (1998).

According to Schweingruber (1988), pine ring-width chronologies in northern Fennoscandia can be synchronized within 800 km. Although a similar pattern of synchronization is supported by the present material (Figure 5), it could be added that in particular it is the high-frequency component of variation that exhibits a drop in inter-correlations after the above-mentioned limit. In addition, correlations between Regions *B* and *D* are poorer than could be expected purely from the distance. This is probably caused by the clear difference between growth response to temperature and precipitation variables between northern and southern boreal forest belts (Figure 4). Time-dependent running correlation between Regions *A* and *D* (Figure 5) clearly shows that although chronologies from these two regions do share periods of significant (positive) synchronization, these periods are interrupted by sudden drops in correlation.

Extreme Years of Growth and Volcanic Forcing

There are no extreme years (determined by the level of 97.5 and 2.5 percentile for positive and negative growth, respectively) common to all regions (Figure 6, Table 1). There are likewise no extremely positive years common to three out of four regions. However, years 1826, 1898 and 1930 are common in Regions *A* and *B*, 1648 in *B* and *C*, and 1922 in *C* and *D*. Years of most suppressed growth are 1601, 1696 and 1806; these years represent annual anomalies of negative ring-width indices in Regions *A*, *B* and *C*, and as a rule of a thumb growth suppression is severer northward. However, in Region *D* all these years represent a

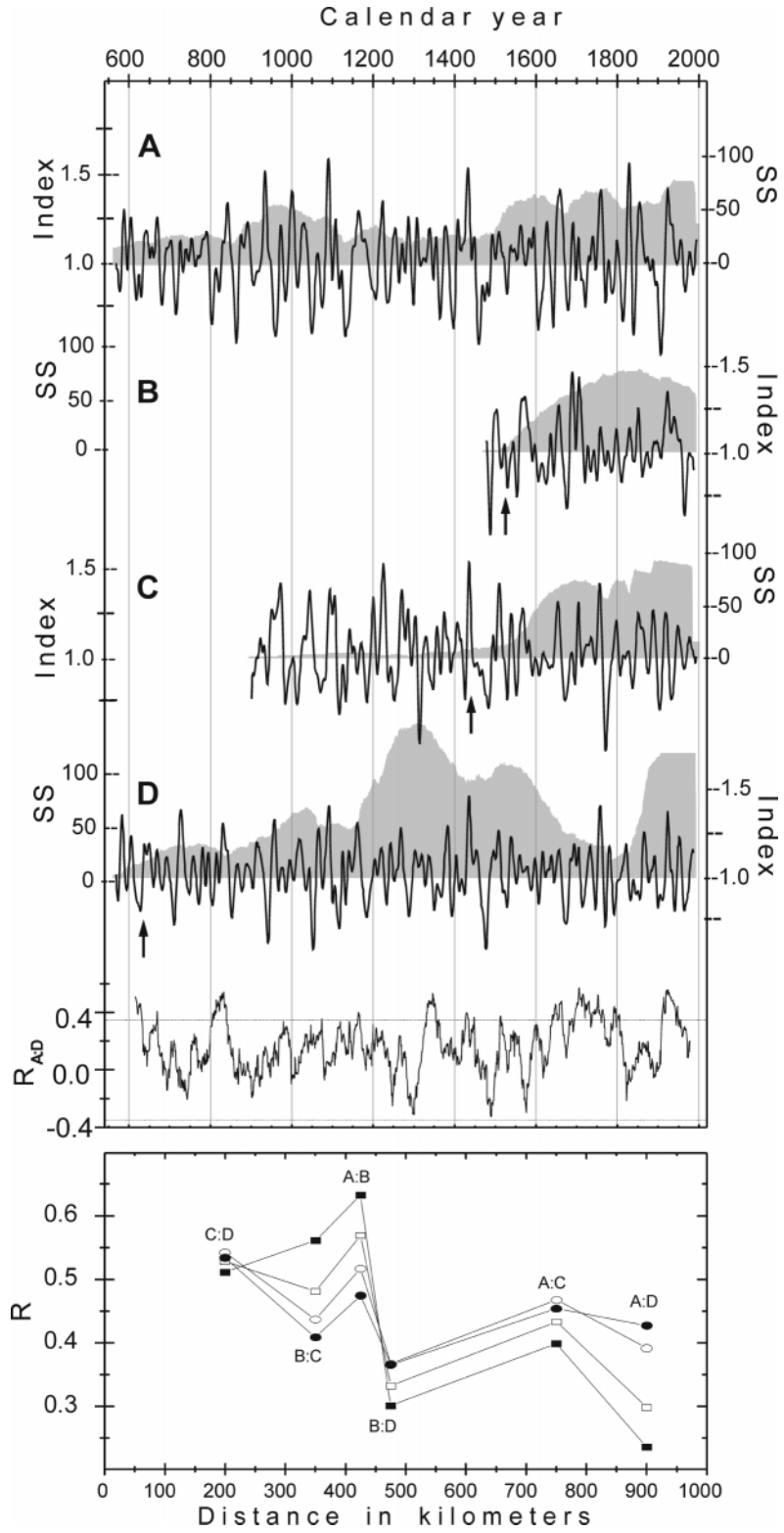
Table 1. Ten most extreme years of growth in different chronologies listed in descending order of amplitude. Number of asterisks (*) indicate the number of joint occurrence with other chronologies.

Positive Extreme Years			
A	B	C	D
1826*	1684	1915	1957
1930*	1826*	1882	1924
1823	1648*	1648*	1890
1689	1655	1954	1694
1964	1702	1752	1934
1626	1898*	1793	1754
1829	1634	1885	1922*
1898*	1707	1922*	1921
1738	1704	1947	1691
1594	1930*	1570	1865
Negative Extreme Years			
A	B	C	D
1601**	1696**	1867	1992
1837	1601**	1696**	1940
1680	1806**	1926*	1889
1806**	1719	1806**	1845
1641*	1641*	1931	1926*
1709*	1709*	1601**	1852
1695	1961	1835	1875
1574	1672	1928	1853
1769	1549	1803	1959
1696**	1580	1790	1969

(slightly negative but) close to average value of growth. During the common period (*i.e.* last five centuries), Region *D* experienced only a single year of a negative growth anomaly jointly with the Region *C* in 1926.

Prior to the common period, Regions *A* and *D* exhibit common extremely negative growth in A.D. 618 and common extremely positive growth in 1405 and 1433. Interestingly, in 1495 pine growth was extremely suppressed in Region *A* and ameliorated in Region *D*.

Figure 5. Variation of four regional chronologies *A*, *B*, *C* and *D*, smoothed with a 20-year Gaussian filter, with corresponding sample size (SS) as grey area. Moving 30-year window correlation between chronologies from Regions *A* and *D* ($R_{A,D}$) is shown underneath the regional chronologies with two horizontal lines representing the level of significance ($p < 0.01$) for correlation. In the lowermost part, correlations (R) between the regional chronologies are separately shown as a function of geographical distance, for residual (filled squares) and standard chronologies (open squares), as well as for 10-year (open circles) and 20-year (filled circles) Gaussian 'low-pass' filtered chronologies.



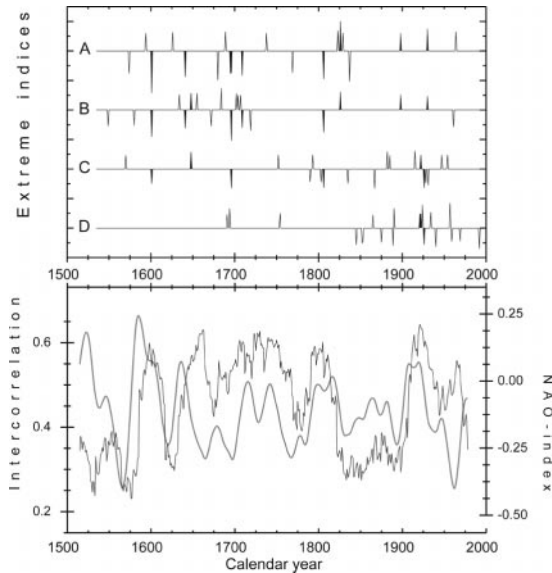


Figure 6. Comparison between most extreme years of growth in each regional chronology (upper panel). Length of each peak shows intensity (strength) of the positive or negative event, and filled peaks show extreme years in at least two regions. Positive years of joint occurrence are 1648, 1826, 1898, 1922 and 1930, whereas corresponding negative years are 1601, 1641, 1696, 1709, 1806 and 1926. In the lower panel, mean correlation between all regional chronologies using a moving 30-year window (thin line), along with North Atlantic Oscillation (NAO) indices (Cook *et al.* 2002) filtered by a 30-year cubic spline function (thick line).

Several of the negative extreme years of growth (Figure 6, Table 1) could be associated with known volcanic eruptions, as shown by Gervais and MacDonald (2001) using the summer temperature sensitive Scots pine ring widths from the Kola Peninsula (see Figure 1). The following years from Table 1 also coincide with eruptions (in parenthesis) reported by Gervais and MacDonald (2001): 1601 (Huaynaputina 1600), 1641 (Koma-ga-Take 1640 and Parker 1641), 1680 (Tongkoko 1680), 1709 (Fuji 1707) and 1837 (Cosiguina 1835). Details of eruptions are compiled by Simkin *et al.* (1981) and Briffa *et al.* (1998). The year 1580, listed in Table 1, coincides with the Billy Mitchell eruption in the same year (see discussion in Briffa *et al.* 1998). In contrast, the negative extreme year 1806 cannot be associated with any single volcanic event known to exert hemispheric influence (see Simkin *et al.* 1981).

All the years of minimum growth index discussed above in connection with volcanic events occurred in Regions A, B or C, and none of them in Region D. That is, lowered summer temperatures, forced by volcanic activity (*e.g.* Kelly and Sear 1984; Bradley 1988) suppressed the pine growth in the regions of northern and middle boreal forest belts (Regions A, B and C), but not in the south (Region D), where the summer temperatures of the concurrent year do not have such an impact on pine growth (see Figure 4). However, one can find 1992 as the first in the list of the most extreme negative growth indices in Region D (Table 1). Even this year could be associated with the recent eruption of Pinatubo during the preceding year, and it was also recorded as the driest early-summer (May–June) at the Lappeenranta weather station (in the vicinity of Region D) during the calibration period used here.

North Atlantic Oscillation

After the reconstruction of the winter NAO-index (Cook *et al.* 2002) and time-dependent common growth signal (mean correlation between all four regional chronologies) for the last five centuries (Figure 6), it seems evident that positive phases of NAO drive common radial growth of pine across Finland. That is, long-term positive phases of NAO coincide with spells of increased common growth signal, and *vice versa*. This joint occurrence is supported by correlations between ring widths and winter NAO shown above (Figure 4), as well as by the observation of Macias *et al.* (2004) who found that the intervals of positive NAO particularly impact pine radial growth in Northern Fennoscandia.

CONCLUSIONS

Four regional ring-width chronologies of Scots pine from Finland were presented. Sampled regions were situated at the northern forest-limit region, and in the northern, middle and southern boreal forest zones. Comparison of tree-ring statistics between the regions showed evidence of a clear ecogeographical gradient through the transect. There was a gradual decline of the common growth signal from north to south, along with in-

dependent indication of increasing growth competition (*i.e.* increased concavity in age-size related growth models) in the same direction. When growth trend modeling of Fritts *et al.* (1969) was used along with a previously defined relationship between inter-tree competition and concavity of pine growth trends (Mikola 1950), the growth-trend modeling was shown to provide a quantitative measure of region-wide competition experienced by pines. Ring-width variance exhibited a distinct drop in mean sensitivity and standard deviation from the forest-limit southward to the other three regions. This change corresponded to a similar drop in the variance explained (R^2) by the meteorological data (temperature and precipitation). However, based on response functions, the three northernmost regions (forest-limit, northern and middle boreal forests) showed a common (positive and significant) impact of mid-summer (July) temperatures on radial growth, whereas a similar effect of temperature was absent in the southernmost region where early-summer (May–June) precipitation contributed the greatest effect on ring widths. Concurrent May precipitation had a positive, significant impact on tree rings in all four regions.

Correlations between chronologies from neighboring regions were highest in the high-frequency band of ring-width variations, whereas chronologies farther apart correlated better in the low-frequency band of growth variability. This may imply that long-term climatic variations were more synchronized over distances in relation to the short-term variations, or, that common variation on decadal and bi-decadal time-scales is contributed by NAO, known to operate at similar frequencies.

Narrow rings were associated with volcanic events over the three northernmost regions. The absence of volcanic signatures in the southernmost region is caused by lack of growth response to summer temperatures. Volcanic effects on tree rings were found to be generally severest in the northernmost regions, where the growth response to summer temperatures was also strongest. As the comparison was made over the last five centuries, the latter response suggests that relative response of pine growth to summer temperatures in all four regions has remained somewhat unchanged over the same period of time.

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REFERENCES CITED

- Ahti, T., L. Hämet-Ahti, and J. Jalas
1968 Vegetation zones and their sections in northwestern Europe. *Annales Botanici Fennici* 3:169–211.
- Akaike, H.
1974 A new look at the statistical model identification. *IEEE Transactions on Automatic Control* AC-19: 716–723.
- Aniol, R. W.
1983 Tree-ring analysis using CATRAS. *Dendrochronologia* 1:45–53.
- Box, G. E. P., and G. M. Jenkins
1970 *Time Series Analysis: Forecasting and Control*. Holden-Day, San Francisco; 553 pp.
- Bradley, R. S.
1988 The explosive volcanic eruption signal in northern hemisphere continental temperature records. *Climatic Change* 12:221–243.
- Briffa, K. R., P. D., Jones, F. H., Schweingruber, and T. J. Osborn
1998 Influence of volcanic eruptions on Northern Hemisphere over the past 600 years. *Nature* 393:450–455.
- Cook, E. R.
1985 *A Time Series Analysis Approach to Tree-ring Standardization*. Ph.D. dissertation, University of Arizona, Tucson; 171 pp.
- Cook, E. R.
1987 The decomposition of tree-ring series for environmental studies. *Tree-Ring Bulletin* 47:37–59.
- Cook, E. R., R. D. D'Arrigo, and K. R. Briffa
1998 A reconstruction of the North Atlantic Oscillation using tree-ring chronologies from North America and Europe. *The Holocene* 8:9–17.
- Cook, E. R., R. D. D'Arrigo, and M. E. Mann
2002 A well-verified, multiproxy reconstruction of the winter North Atlantic Oscillation Index since A.D. 1400. *Journal of Climate* 15:1754–1764.
- Cook, E. R., and K. Peters
1981 The smoothing spline: A new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bulletin* 41:45–53.

- D'Arrigo, R. D., E. R. Cook, G. C. Jacoby, and K. R. Briffa
1993 NAO and sea surface temperature signals in tree-ring records from the North Atlantic sector. *Quaternary Science Reviews* 12:431–440.
- Eronen, M., P. Zetterberg, K. R. Briffa, M. Lindholm, J. Meriläinen, and M. Timonen
2002 The supra-long Scots pine tree-ring record for northern Finnish Lapland—Part 1: chronology construction and initial inferences. *The Holocene* 12:673–680.
- Fritts, H. C., J. E. Mosimann, and C. P. Bortorff
1969 A revised computer program for standardizing tree-ring series. *Tree-Ring Bulletin* 29:15–20.
- Fritts, H. C., D. G. Smith, C. A. J. W. Cardis, and C. A. Buidelsky
1965 Tree-ring characteristics along a vegetation gradient in Northern Arizona. *Ecology* 46:393–401.
- Gervais, B. R., and G. M. MacDonald
2001 Tree-ring and summer-temperature response to volcanic aerosol forcing at the northern tree-line, Kola Peninsula, Russia. *The Holocene* 11:499–505.
- Heino, R.
1994 Climate in Finland during the period of meteorological observations. *Finnish Meteorological Institute Contributions* 12:1–209.
- Henttonen, H.
1984 The dependence of annual ring indices on some climatic factors. *Acta Forestalia Fennica* 186:1–38.
- Holmes, R. L.
1983 Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin* 43:69–75.
- Holmes, R. L., R. K. Adams, and H. C. Fritts
1986 *Tree-Ring Chronologies of Western North America: California, Eastern Oregon and North Great Basin with Procedures Used in the Chronology Development Work Including Users Manuals for Computer Programs COFECHA and ARSTAN*. Chronology Series VI. Laboratory of Tree-Ring Research, University of Arizona, Tucson.
- Hurrell, J. W.
1995 Decadal trends in the North Atlantic Oscillation and relationships to regional temperature and precipitation. *Science* 269:676–679.
- Hustich, I.
1948 Scotch pine in northernmost Finland and its dependence on the climate in the last decades. *Acta Botanica Fennica* 42:1–75.
- Kelly, P. M., and C. B. Sear
1984 Climatic impact of explosive volcanic eruptions. *Nature* 311:740–743.
- Lindholm, M.
1996 *Reconstruction of Past Climate from Ring-width Chronologies of Scots Pine (Pinus sylvestris L.) at the Northern Forest Limit in Fennoscandia*. Ph.D. dissertation, University of Joensuu, Publications in Sciences 40; 169 pp.
- Lindholm, M., Ó. Eggertsson, N. Lovelius, O. Raspopov, O. Shumilov, and A. Läänelaid
2001 Growth indices of North European Scots pine record the seasonal North Atlantic Oscillation. *Boreal Environmental Research* 6:275–284.
- Lindholm, M., H. Lehtonen, T. Kolström, J. Meriläinen, M. Eronen, and M. Timonen
2000 Climatic signals extracted from ring-width chronologies of Scots pine from the Northern, Middle and Southern parts of the boreal forest belt in Finland. *Silva Fennica* 34:317–329.
- Lindholm, M., J. Meriläinen, and M. Eronen
1998 A 1250-year ring-width chronology of Scots pine for south-eastern Finland, in the southern part of the boreal 1999 forest belt. *Dendrochronologia* 16–17:183–190.
- Macias, M., M. Timonen, A. Kirchhefer, M. Lindholm, M. Eronen, and E. Gutierrez
2004 Growth variability of Scots pine along a West-East gradient across Northern Fennoscandia: a dendroclimatic approach. *Arctic, Antarctic and Alpine Research* 36:565–574.
- Mikola, P.
1950 Puiden kasvun vaihteluista ja niiden merkityksestä kasvututkimuksessa. Summary: On the variations in tree growth and their significance to growth studies. *Communications Instituti Forestatis Fenniae* 38:1–131.
- Mirov, N. T.
1967 *The Genus Pinus*. Ronald Press, New York; pp. 602.
- Monserud, R. A.
1986 Time-series analyses of tree-ring chronologies. *Forest Science* 32:349–372.
- Osborn, T. J., K. R. Briffa, K. R., and P. D. Jones
1997 Adjusting variance for sample-size in tree-ring chronologies and other regional mean timeseries. *Dendrochronologia* 15:89–99.
- Rogers, J. C.
1984 The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. *Monthly Weather Review* 112:1999–2015.
- Schweingruber, F. H.
1988 *Tree Rings. Basics and Applications of Dendrochronology*. Kluwer Academic Publishers, Dordrecht, Holland; 276 pp.
- Simkin, T. L., S. L. McClelland, D. Bridge, C. Newhall, and J. H. Latter
1981 *Volcanoes of the World*. Hutchinson Ross, Stroudsburg, Pennsylvania; 232 pp.
- van Deusen, P. C.
1990 Popular formulations for modeling tree rings from climate: a unifying approach. *Journal of Environmental Quality* 20:823–827.
- Wigley, T. M. L., K. R. Briffa, and P. D. Jones
1984 On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climatology and Applied Meteorology* 23:201–213.

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