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A ring-width chronology of Scots pine from northern Lapland covering the last two millennia

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We have built a reliable ring-width chronology of Scots pine (*Pinus sylvestris* L.) in northern Lapland, starting from the year 50 AD and covering the last two millennia. The chronology is built from 68 living trees and 274 dead trees, collected between 68°–70° N and 21°–30°E. The bulk of the data from dead trees has been published previously. In these earlier works the chronology was built without standardizing the series. We have now rebuilt the chronology using proper analytical tools. Thus the interpretations have also been revised. Periods of enhanced and suppressed pine growth in the northern timberline region during the last two millennia are presented. A comparison is also made between the northern chronology and a millennial chronology from south-eastern Finland. Moreover we apply means of measuring the strength of the common 'signal' in tree-ring chronologies and chronology reliability as a function of time.

Key words: dendrochronology, growth variability, Scots pine, tree-ring width

INTRODUCTION

The bulk of the data used here has been published previously (e.g., Zetterberg *et al.* 1994, 1996). In these earlier works the chronology was built without standardizing the measurement series before averaging. Since this procedure leaves the mean and variance of the individual measurement series unstable, we have now rebuilt the chronology using proper analytical tools. Consequently, the interpretations have also been revised. Applying rather stiff splines in standardization may result in a loss of long-term variance. However, this loss is meaningless compared with the advantage of avoiding the error ('noise') caused by averaging unstandardized time series.

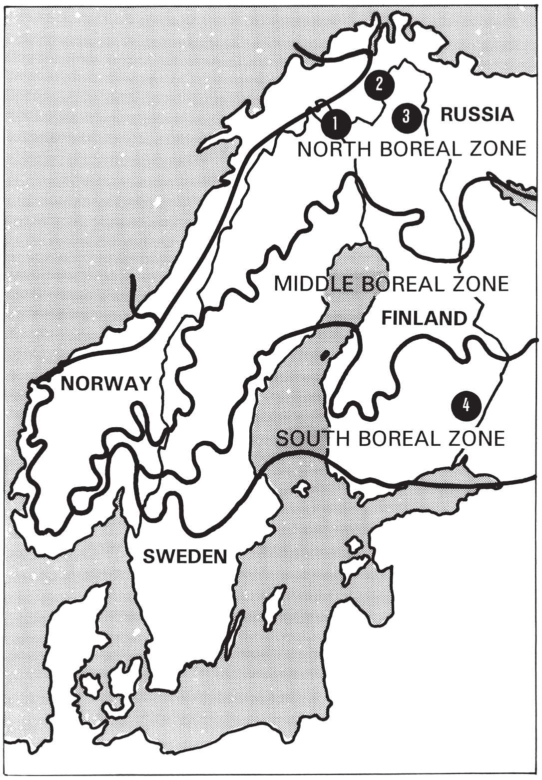

Fig. 1. Research areas. The sites in the north (1–3) are located between 68°–70°N and 21°–30°E. The southern site (4) is located between 61°–62°N and 29°–30°E. The boreal forest belt may be divided into a northern, middle, and southern zone.

A common goal among dendrochronologists is to build chronologies in a way that preserves as much long-term, or low-frequency, variance as possible. Since tree-growth and growth forcing environmental factors (e.g., climate) are expected to consist of inter-annual, inter-decadal, inter-centennial and even longer scale modes of variance, this kind of chronology would then enable the investigation of growth variability and changing climate in the long run. The long chronologies may also create a basis for analyzing forest health by using dendroecological techniques to assess the rate, timing, and magnitude of changes in growth rates (Fritts & Swetnam 1989, Spiecker *et al.* 1996).

Scots pines growing under extreme conditions in the regions of the northern timberline are known to have a strong common 'signal', which is empirically linked to temperature forcing (e.g., Briffa *et al.* 1990, Lindholm *et al.* 1996). Going from north to south, tree-growth becomes less affected by growing seasonal temperatures, and more affected by e.g., precipitation (Lindholm *et al.* 1997). Compared with the northern timberline, factors related to stand dynamics increase in importance in controlling annual growth variability of southern pines. Towards the south, the correlations between the diameter growth of pine and climate variability are expected to become weaker. Likewise, the variation in the width of annual rings should become smaller.

MATERIAL

The research area (Fig. 1) as well as sampling, preparation of samples and measurement of the subfossil data were described in detail by Zetterberg *et al.* (1994, 1996) and Eronen *et al.* (1996). This data set consists of samples from subfossil trees as well as samples from an old building, 265 mean tree-ring series in all, collected between 68°–70°N and 21°–30°E. We have now added samples from 68 living trees (Lindholm *et al.* 1996). In addition, we have used samples from the old Sodankylä Parish church, nine beams in all.

In comparisons of northern and southern data sets, we have used ring-width data from southeastern Finland described by Lindholm *et al.* (1997). These data were sampled from 48 living trees and 91 pieces of subfossil and construction timbers. The southern research area covers a region surrounding the central parts of the Lake Saimaa basin, between 61°–62°N and 29°–30°E.

METHODS

Ring-width measurements and cross-dating

Cores from living trees and old buildings were mainly extracted by an increment borer. The samples taken from lake-bottom trunks, were sawn and taken as disks after lifting the trunks to the surface. Ring widths were measured to the nearest 0.01 mm. The measured series were then cross-dated by visual comparison of ring-width graphs on the light table. We also computed cross-correlations between individual series using several procedures (Holmes *et al.* 1986, Deusen & Koretz 1988, Aniol 1989). Cross-dating is one of the basic practices in tree-ring analysis. The concept refers to the general year-to-year agreement or synchrony (correlation) between variations in tree-ring series taken from different sides of a tree, or between different trees or among different site chronologies. According to Fritts (1976), this synchrony is evidence for a limiting effect of climatic variation on tree growth.

The indices were also checked on the computer screen after standardization in order to detect possible distortions at the ends or at the beginnings of the series. This procedure resulted in the elimination of 5 to 15 years from 20 samples in all.

A conceptual model of factors affecting tree growth

The idea of a tree as an integrator reacting to environmental factors has led to the decomposition of radial growth into its components in a linear fashion (Graybill 1982, Cook 1987, Fritts & Swetnam 1989). Although such models are simplistic and theoretical, they can help understanding and distinguishing between the major sources of ring-width variation. The following model formulation, based on Cook (1987, 1990), reduces annual radial growth to five discrete classes of signals as a function of time:

$$R = A + C + D_1 + D_2 + E \quad (1)$$

where: R = the measured and dated ring-width series of a tree; A = the biological growth curve or age-size related trend in ring-width; C = the climatic signal common to a stand of trees; D_1 = local disturbance pulse within a forest stand; D_2 = a larger scale disturbance pulse, originating from outside the stand, and E = unexplained variability, including measurement error.

Standardization

In standardization, the main goal is to emphasize the desired 'signal' and to reduce the unwanted elements of 'noise'. In this study, we have defined 'noise' as a removable growth trend of nonclimatic factors (G), viz. $G = A + D_1 + D_2$. Standardization is then achieved by division:

$$\text{Index} = R/G \quad (2)$$

where R is the observed and G is the expected growth in any given year. Since local variance of a non-stationary ring-width series is roughly proportional to its local mean, the procedure of dividing each ring-width by a fitted curve value is meant to stabilize the variance simultaneously with the mean (Fritts 1976, Cook *et al.* 1990). Averaging also reduces part of the 'noise'.

We applied a pragmatic approach in modeling the growth trend, the 'noise' component to be discarded as G. The nonclimatic sources of variation in the data were modeled collectively as splines. It was assumed that the removed low frequency variance consists mainly of noise. However, there is a potential loss of meaningful long-term variance. We used rather stiff splines (67%), passing 50% of the variance of the series at frequencies greater than two thirds of the series length (Cook & Peters 1981).

Measuring signal strength and chronology reliability

We have used mean interseries correlation (RBar or $\bar{r}_{\text{bt}}$) as a measure of the strength of the common growth 'signal' within the chronology (Wigley *et al.* 1984, Briffa & Jones 1990). This index was calculated over a moving 30-year window beginning from the year 50 AD, when sample depth (replication) is at least 4. For this purpose, we produced a single mean time series for each tree. We also calculated the Expressed Population Signal (EPS), which is expected to measure chronology reliability. EPS is a function of RBar and the series replication, according to the following equation (Wigley *et al.* 1984, Briffa & Jones 1990):

$$\text{EPS}(t) = \frac{\bar{r}_{\text{bt}}}{\bar{r}_{\text{bt}} + (1 - \bar{r}_{\text{bt}})/t} = \frac{t\bar{r}_{\text{bt}}}{t\bar{r}_{\text{bt}} + (1 - \bar{r}_{\text{bt}})}$$

where t is the number of tree-ring series averaged (one core per tree) and $\bar{r}_{\text{bt}}$ (or identically RBar) is the mean between-tree (bt) correlation.

RESULTS

Quality of the chronology

The cross-datings of the 342 samples are presented in Fig. 2. The time spans of individual mean-tree

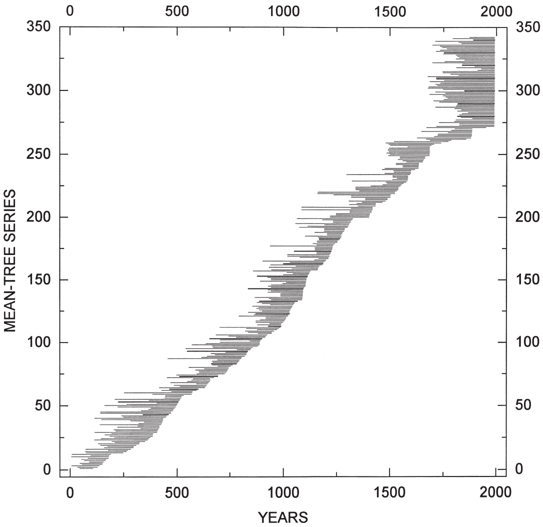

Fig. 2. Time spans of the individual pine ring-width series included in the final chronology, sorted by the youngest ring of the sample.

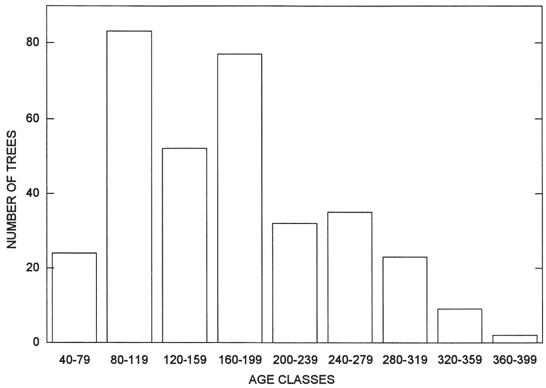

Fig. 3. Age distribution of the trees included in the chronology in 40-year age classes. Since the living trees were sampled at breast height and the dead trees did not always have bark, leaving several rings out of calculation, the ages are slightly underestimated.

series are ordered from the youngest at the top to the oldest at the bottom. The coverage is fairly good for the whole period. Fig. 3 demonstrates the age distribution of the individual trees included in the chronology. The grand mean age of all sampled trees is 169 years (SD = 73). This value is a slight underestimation of the ages, since living trees were sampled at breast height, which yields breast-height age. In addition, the dead trees did not always have bark, leaving several rings out of the calculation.

The common 'signal' measured by RBar is rather strong for the whole period under investigation. RBar has a mean of 0.42 (SD = 0.14) (Fig. 4, lower plot). Judged from EPS values, the chronology is also very reliable. Wigley *et al.* (1984) and Briffa and Jones (1990) report values over 0.85 to be satisfactory for dendroclimatological purposes. Our chronology shows values well above that, the grand mean of EPS being 0.91 (SD = 0.18).

Long-term growth variability

The ring-width chronology from northern Lapland is presented in Fig. 4. It covers the years from 50 to 1993 AD. Inter-annual, as well as lower frequency variance is clearly evident. However, it is not reasonable to expect much over 110-year trends to be detected in the chronology, since we have used 67% splines in standardizing series with a mean of 169 years. This procedure preserves the bulk of the variance, which is less than two thirds of the series length.

Table 1 lists periods of enhanced and suppressed growth experienced by northern pines during the last two millennia. Only periods when index values stayed below or above average for 10 years or more are included. In Fig. 4 (uppermost plot), multidecadal variability (lower frequencies) is emphasized using 20-year centered moving averages. This smoothed line can be used as a modern yardstick against which to compare the magnitude and duration of changes in growth variability over the past two millennia.

Comparison of growth variability between the northern and southern parts of the boreal forest belt during the second millennium AD

Fig. 5 shows a comparison of growth variability between the northern and southeastern parts of the boreal forest belt in Finland since the year 1 000 AD. These two regions represent the opposite ends of the boreal zone, the distance between them being over 800 km. The two regional chronologies, which were standardized the same way,

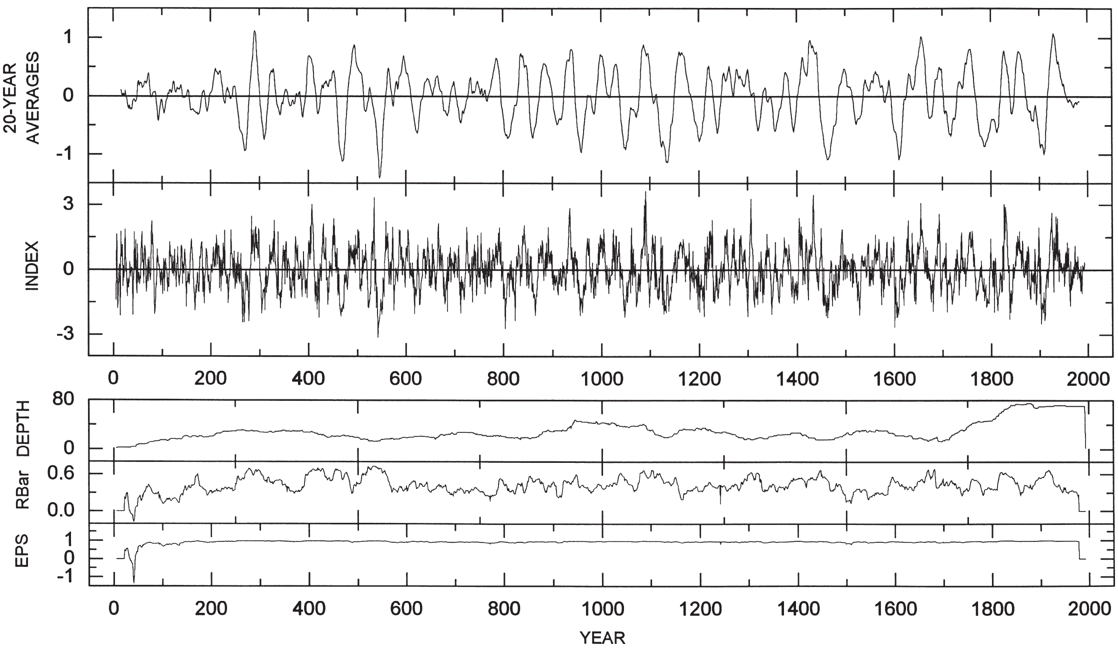

Fig. 4. A master ring-width chronology of Scots pine from northern Finnish Lapland, from 50 to 1993 AD. A smoothed line is presented to emphasize long-term (low frequency) variability. The mean inter-series correlation (RBar) is a measure of the common growth 'signal'. Expressed Population Signal (EPS), a function of RBar and the series replication, express chronology reliability. RBar is calculated between all samples over a moving 30-year window.

Table 1. Over 10-year periods of above and below average growth since the year 50 AD in northern Lapland.

Above average		Below average	
First millennium	Second millennium	First millennium	Second millennium
204–217	1082–1095*	165–177	1044–1057
281–312	1155–1171*	263–280	1071–1081
319–333	1371–1381	462–481	1127–1146*
399–412	1424–1439	539–555	1200–1211
482–494	1533–1542	709–722	1312–1322
782–795	1558–1573*	800–813*	1360–1370
871–880	1647–1662	858–870*	1388–1401
887–897	1684–1694	898–913	1456–1467
931–939	1752–1766*	952–968	1521–1532
994–1008	1847–1865		1601–1612*
	1918–1927		1615–1624
	1930–1939		1672–1683
			1708–1724
			1767–1776
			1781–1796
			1810–1822
			1878–1889
			1902–1915

* Over 10 years of overlap with the 10 largest temperature anomalies (using 20-year means) provided by Briffa *et al.* (1990).

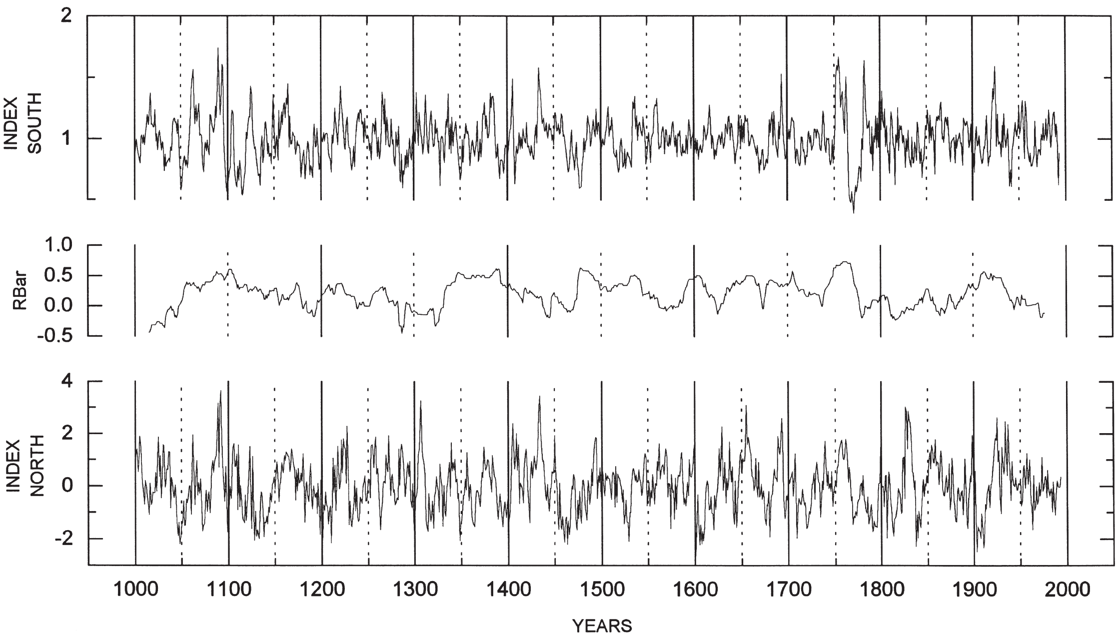

Fig. 5. Comparison of northern and southern chronologies over the second millennium. Correlation between the two is 0.32 for the whole period. The strength of the common signal between the two curves is expressed as RBar as a function of time. Both chronologies were standardized the same way, using equally stiff splines.

synchronize rather well with each other. Correlation between the two chronologies over the last 993 years is 0.32. The strength of the common signal between the two chronologies as a function of time is expressed as RBar in Fig. 5. Although the correlation is mainly positive, there are also several anti-correlation peaks.

The two chronologies vary similarly both in higher and lower frequencies. Common long-term trends are conspicuous especially during mid-centuries (around the dotted lines in Fig. 5). High-frequency similarities are clearly evident around several pointer years, e.g., 1050, 1075, 1210, 1350, 1395, 1550, 1770, and 1840.

DISCUSSION

Comparison with reconstructed climatic variations

Our chronology was compared with a 1 400-year tree-ring record of summer temperatures in Fennoscandia by Briffa *et al.* (1990). This reconstruction was made for northern Sweden from ring-width and maximum-density chronologies of Scots pine. Briffa *et al.* (1990) listed the coldest and warmest 20-year means, which match well with the periods of above and below average growth in our chronology. In Table 1, we have marked with an asterisk the eight periods, out of the ten provided by Briffa *et al.* (1990), which have at least ten years of overlap with our results. The two disagreements in the two records took place in the 750s–760s and the 1350s.

Change in climate forcings from the north to the south

The present work shows evidence that a common climatic forcing influences the northern and southern pine stands. Interestingly, the signal shows opposite features as well. Significant negative RBar values are evidence for growth inversions, which may be caused by climatic inversions. During some periods, growth conditions seem to have been favorable in the south, while they have been unfavorable in the north.

It is noteworthy that the variability of radial growth clearly decreases, i.e. the variance of ring-width series becomes smaller, going from the north to the south. In a previous article (Lindholm *et al.* 1996), we have confirmed the results of earlier studies (e.g., Briffa *et al.* 1990) showing that growing seasonal temperatures govern the growth rates of northern pines. We have also demonstrated that towards the south tree-growth becomes less affected by temperatures, and more affected by e.g., precipitation (Lindholm *et al.* 1997).

Origin of variability

A comparison between northern (Lindholm *et al.* 1996) and southern (Lindholm *et al.* 1997) pine stands in terms of growth responses to climatic factors have revealed similarities as well as differences. In both regions, precipitation during the previous August appears to have a positive and significant impact on growth while precipitation in November has a negative effect. In southeastern pines, precipitation in January has a negatively significant and in June a positively significant influence on growth. While the temperature in June and July exerts a significant positive effect in the north, both May and June temperatures seem to suppress growth in the southeastern pines. In addition, temperature of the previous August has a negative influence and during the current March, a positive impact on growth in the south-east.

CONCLUSIONS

Northern pines have not experienced unprecedented changes in growth during the present century on interannual-to-multidecadal timescales. In the past there exists several periods equal to the drastic decline in growth in the early 1900s, the relatively high productivity in the 1920s–1930s, and the post-1950 decline.

Knowledge of changes in growth and climate on timescales from one to several hundreds years, especially during the recent millennia is of crucial importance for providing a context within which to analyze the variability that has been observed during the present century. The proxy tree-ring records provide an indication of natural (pre-anthropogenic) growth and climate variability, either singly at specific geographical locations or in combination on continental and perhaps even hemispheric scales.

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