Summary of the strengths and weaknesses of the millennial tree-ring archive of Fennoscandian forest-limit Scots Pine

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Geographic distribution of the archive

Tree-ring samples of Scots pine (*Pinus sylvestris* L.) were collected from living trees, dead standing logs, old buildings, and subfossil wood from small lakes (Eronen *et al*. submitted), selected dataset containing at present 1081 tree-ring series in all. The latter archive is the major source of samples. The area is situated between 68° and 70° N, 20° and 30° E, located in the northern part of the boreal forest belt in Fennoscandia, between the Swedish Scandes and the Kola Peninsula (Eronen *et al*. submitted). The forest limit region refers to the transition zone of relatively open canopy pine forests, between treeless tundra in the North and mixed Norway spruce (*Picea abies* (L.) Karsten) and pine forests in the South. Northern Sweden at similar latitudes, Lake Torneträsk area, is a source of Scots pine tree-ring chronology almost equal in length (Grudd *et al.* submitted). However, this paper is focused on the Finnish tree-line chronology.

Geographic distribution of the archive is limited by the necessity (uniformitarian assumption) of having uniform growth responses and growth patterns in the data. Homogeneity of tree-ring data from the region have been demonstrated by comparison of chronologies built from standing (living) trees (Lindholm 1996). Highly consistent tree-ring chronologies may be built from diverse sites as well as from various age-classes of trees (Lindholm *et al*. 2000; Lindholm *et al*. submitted).

Temporal range

Pine immigrated to northern Finnish Lapland by 7500-7000 B.C. and immediately spread beyond its present limits (Eronen 1979). At the present, the northern Finnish pine chronology spans from 5520 B.C. to 2001 A.D. The elongation of the chronology could be possible because there is a long gap in time between the end of the tree-ring chronology and immigration of pine. On the other hand, it could be possible that the conditions for preservation of subfossil pines were not favourable in the earlier Holocene time before c. 5500 B.C.

Range of resolution

Annual resolution in tree-ring data is due to procedure of cross-dating, which is a basic principle in dendrochronology. Interannual-to-decadal scale variability is most easily resolved by most methods of building chronologies. Centennial and even millennial scale variability has recently been extracted successfully from the northern data by a method called Regional Curve Stardardization (RCS) (Helama *et al*. submitted).

Climate variables reconstructed

A calibration procedure by multiple regression over the common period of tree-ring and weather data can be employed to obtain transfer function to estimate predictand variables from a set of predictors, that is, mid-summer temperatures from tree rings. The proof of validity of results is yielded by various routine statistical procedures by comparing actual independent climatic data to reconstructed variables.

From all monthly climatic variables, radial growth of northern tree-limit pines (tree-ring width) correlates most significantly with concurrent mean July temperatures over the region under study. This particular relationship (tree radial growth/mean July temperature) becomes weaker the more south the collected samples are in origin (Lindholm *et al*. 2000). In the former studies, approximately 40 to 50 percent of independent mid-summer temperature variations were to be captured by the transfer models constructed by the single tree-ring width chronology.

Climate related variables reconstructed

North Atlantic Oscillation (NAO) was reconstructed using the network of boreal forest belt pines (tree-ring widths) from North Europe over the secular period, the material originating mainly as Finnish and North-west Russian (Lindholm *et al*. 2001). This bears the possibility that reconstruction could be expanded over the last millennia in the future, after the complement of the network of long tree-ring chronologies from southern and northern boreal zones.

Uncertainties of reconstruction

Reports of possibly reduced sensitivity of recent tree-growth to temperature at high northern latitudes (Briffa *et al*. 1998) may influence the applicability of the present transfer models. During the second half of the twentieth century, the decadal-scale trends in wood density and summer temperatures have increasingly diverged as wood density has progressively fallen. The cause of this increasing insensitivity of wood density to temperature changes is not known, but past temperatures could be overestimated if it is not taken into account in dendroclimatic reconstructions. Moreover, the recent reduction in the response of trees to air-temperature changes would mean that estimates of future atmospheric CO_2 concentrations based on carbon-cycle models which are uniformly sensitive to high-latitude warming could be too low. Intensive studies of possible instabilities of tree-growth/climate forcing on the key region however remain to be executed.

Key problems of dating/ chronology

During the chronology construction, it was extremely difficult to bridge a gap c. 300 years long in the master chronology. This gap occurred for the period prior to 165 B.C. between the younger, absolutely dated, and older ‘floating’ part of the chronology. A few years ago the gap was bridged and the ‘floating’ part of the chronology was absolutely dated (Eronen *et al*. submitted).

More collected and measured samples are needed for the chronology. In the present chronology, the annual sample replication exceeds the number of 30 (which is generally thought as statistically large sample) over the 36 percent of the total chronology length. Approximately 13 percent of the total chronology length is covered by ten or less samples.

Some other key weaknesses/ strengths

The most notable weaknesses of the northern millennial chronology are related to representativeness or chronology confidence during some critical periods. The confidence of a chronology may be measured as a function of sample replication (the number of samples annually present) and signal strength (measured as correlation between samples). Extraction of greatest amount of low-frequency climatic variation from chronology requires the use of a single expected growth curve to capture tree-ageing trend from individual samples. In so doing, more samples are required to obtain the same level of reliability in the resulting chronology compared to utilization of individually derived standardization curves of expected growth to each sample.

Most important research needs to improve reconstructions

To measure intra-annual ring density (1), because of the excellent temperature response of maximum latewood density variable used together with ring-widths. Increasing sample replication (2) by roughly doubling the number of samples presently used in building the chronology (see above). Increasing the number of samples and updating the modern data set are also needed for development and application of the RCS method (3).

Potential problems in making comparisons between sites (e.g. lake to lake) and between archives (e.g. lake to bog, bog to dry-land)

The most relevant data sets to be compared generally do not have the ideal match of (1) response to the same climatic variables, (2) compatible resolution, and (3) meaningful spatial and temporal cover.

Pines growing in different micro environments in the same region show different growth curves, that is, their decline due to tree ageing is slower on dry and hard lands compared to trees growing in the shoreline (subfossil material from small lakes) (Helama *et al.*submitted). The collection of modern samples from near shoreline zone of small lakes is therefore preferable for further investigations.

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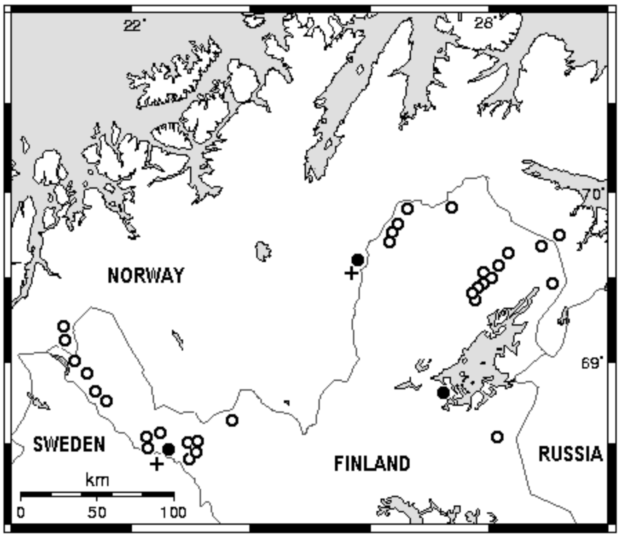

Fig. 1. The sampling sites in northernmost Fennoscandia. Living Trees were sampled at sites marked with black circles. Pine subfossils were sampled at empty circles. The meteorological stations available with c. 120 years of meteorological data for calibration are denoted as crosses.

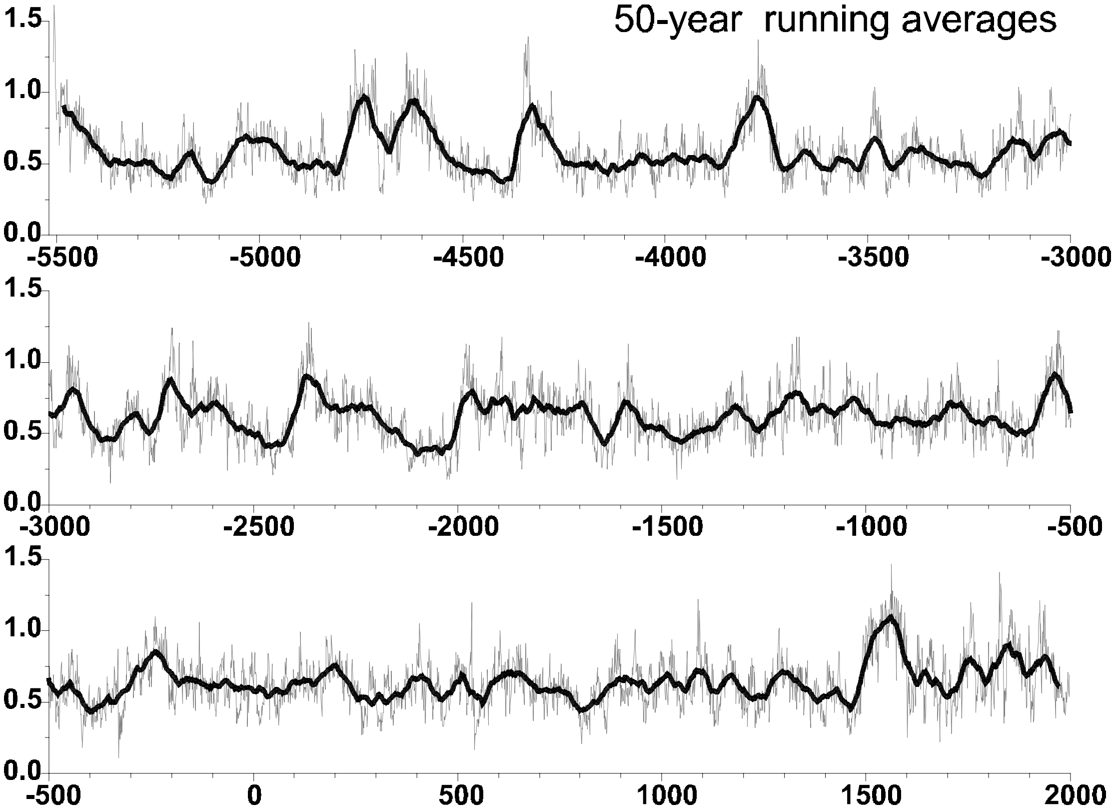

Fig. 2. The Finnish Lapland pine tree-ring chronology (mean raw data), extending back to 5520 B.C. The average ring width remains relatively constant, at about 0.6 mm, throughout the whole chronology. Thin line shows the annual variability.

N:o	Location name	National coordinates		elevation
		Y	X	a. s. l.
1	Ailakkavaaran lompolo	7664.5	258	515
2	Vallijärvi	7633	280.5	465
3	Eteläinen Haukijärvi	7625.5	297	465
4	Pohjoinen Haukijärvi	7626.5	297	475
5	Tsohkkajärvi	7627.5	298	505
6	Hattulompolo	7621.6	362.7	385
7	Läntinen Ladnajärvi	7635.5	276.7	481
8	Itäinen Ladnajärvi	7635.5	277.5	487
9	Kelottijärven suo	7615.5	296.1	375
10	Luossakoadneljärvi	7751.5	475	110
11	Ailigasjärvi	7759.3	502.7	75
12	Koadnelveijavri	7755.5	477.9	109
13	Puollimvarrimlompolo	7734	580.8	160
14	Njargaväärijärvi	7710.3	584.5	220
15	Lujapuoli_210	7710.4	585.2	210
16	Lujapuoli_220	7710.7	584.7	220
17	Tsehajaaurads	7701.5	526.6	197
18	Ooggusjdaurats	7702	526.2	160
19	Ulasjärven lompolo	7699	523.4	199
20	Sammuttivaaran järvi	7694.7	520.8	207
21	Namatesjavren lompolo	7690.8	518.8	215
22	Annanjärvi	7699	523.9	205
23	Namatesjavri	7690.7	518.8	207
24	Loassamlompolo	7700.6	528.7	197
25	Loassamlompolo_kapea	7700.2	528.3	201
26	Aulinlompolo	7700.5	528.3	207
27	Kämppälompolo	7714	540.5	197
28	Selkäjärvi_B	7717.8	542.4	208
29	Vuotkimlompolo	7701.1	528.4	205
30	Pieni Vuotkimlompolo	7701.3	528.5	202
31	Halti	7406.1	581.7	293
32	Koierivaara	7602.4	512	250
33	Härkäjoki (Pelkosenniemi)	7473.1	514.5	165
34	Kaamasmukka	7689.3	499.5	190
35	Kalmankaltio2	7593.9	403.8	340
36	Kalmankaltio1	7595.6	405.3	345
37	Kalmankaltio3	7593.9	403.8	340
38	Kielkajoki	7689.3	499.5	190
39	Kilpisjärvi	7664.5	258	515
40	Koierivaara	7602.4	512	250
41	Koivumukkajärvi	7689.3	499.5	190
42	Kolmiloukkonen (Salla)	7406.1	581.7	293
43	Kompsiovaara	7604	547.1	190
44	Kompsiojärvi (Rajajooseppi)	7604	547.1	190
45	Kultimajärvi1 (Enontekiö)	7604	335	334
46	Laanila	7599	512	280
47	Luolavaara	7598.5	541.5	200
48	Luolajärvi1 (Rajajooseppi)	7598.5	541.5	200
49	Luttojoki (Saariselkä	7595	525	280
50	Kuntsavaara (Muotkanruoktu)	7698	496	190
51	Näkkälä1	7617.1	359.8	370
52	Näkkälä2	7610.2	349.9	349
53	Näkkälä4	7627.8	367.1	440
54	Guoppalampi	7737.3	476.4	147
55	Nuvvosmohkki	7745.3	469.8	130
56	Gardebärvarri_I	7675.1	904	490
57	Peltovuoma (Kittilä)	7589.9	402.5	337
58	Petsimjärvi (Muotkanruoktu)	7689.3	499.5	190
59	Pitkäjärvi (Pallastunturi)	7578.2	376.5	290
60	NäkkäläPS	7610.1	356.2	350
61	Puljunpalonlammit1 (Pelkosen)	7467.1	517	160
62	Pättikkä	7625.4	286	400
63	Riekkovaara (Saariselkä)	7599	512	280
64	Riekkojärvi (Rajajooseppi)	7608	545.3	190
65	Saivojärvi (Ylläs)	7497.4	368.5	170
66	Utsjoki	7751.5	475.1	100
67	Vallijärvi	7632.3	280.3	465
68	Hangasmaa (Ylläs)	7514.1	381.5	265
69	Äkäsjärvi (Ylläs)	7528.5	378.3	265