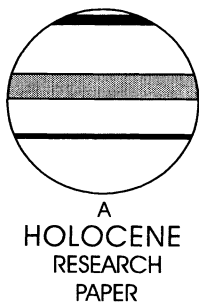


Past changes in the Scots pine forest line and climate in Finnish Lapland: a study based on megafossils, lake sediments, and GIS-based vegetation and climate data

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Abstract: Subfossil samples of Scots pine (*Pinus sylvestris*) and evidence of pine stomata and pollen accumulation rates from previously studied lakes located beyond the present pine forest line in Finnish Lapland were used to reconstruct the extent of the past forest line and the corresponding minimum shift in mean July temperatures, compared with the present. The location of the present pine forest line follows the c. +12.2°C mean July temperature isoline (1961–1990). When minimum shifts in mean July temperatures during the Holocene were studied, the estimated glacio-isostatic land uplift and its regional differences were taken into account. Results indicate that pine reached its maximum distribution between 8300 and 4000 cal. yr BP. The inferred minimum shift in mean July temperature was at that time c. +2.5°C. Until 3000 cal. yr BP, the results indicate a shift of c. +1°C. Between 2538 and 1721 cal. yr BP, evidence for a wider distribution of pine in Finnish Lapland is lacking. During the ‘Mediaeval Warm Period’ the reconstructed minimum shift in mean July temperature was +0.5°C. The record of subfossil pines beyond the present pine treeline ceases during the initiation of the ‘Little Ice Age’, c. 700 years ago.

Key words: Pine, Holocene, treeline, Finnish Lapland, megafossils, palaeoclimate, GIS.

Introduction

The postglacial history of Scots pine in Finnish Lapland has been reconstructed from pollen analysis of lake sediments and peat deposits (Aario, 1943; Hyvärinen, 1975, 1976; Seppä, 1996). The former pine distribution above the present coniferous forest line has been documented by subfossil pines that have been preserved for thousands of years in shallow lakes, ponds, peat deposits, but also in sand and on mineral ground (Eronen, 1979; Eronen and Huttunen, 1987; Eronen and Zetterberg, 1996). According to pollen studies, pine invasion into Finnish Lapland took place at c. 9000 cal. yr BP (Hyvärinen 1975, 1976; Seppä, 1996). The maximum extent and density of pine forest occurred at c. 8000–4000 cal. yr BP, after which the pine retreated gradually to its present forest line.

Quantitative temperature reconstructions from Finnish Lapland have been derived from diatoms (Korhola *et al.*, 2000), chironomids (Korhola *et al.*, 2002; Seppä *et al.*, 2002), pollen (Seppä and Birks, 2001, 2002) and from tree-ring widths (Helama *et al.*, 2002). The highest reconstructed mean July temperatures occurred between c. 6800 and 5300 cal. yr BP (Korhola *et al.*, 2000), between c. 8300 and 3800 cal. yr BP (Seppä *et al.*, 2002), between 8000 and 6500 (Seppä and Birks, 2001, 2002), between 8000 and 5800 (Korhola *et al.*, 2002) and between 3000 cal. yr BP and present (Helama *et al.*, 2002). Even though the absolute values of the reconstructions differ, chironomids from Toskaljavi (Seppä *et al.*, 2002) and pollen (Seppä and Birks, 2001, 2002) show a relatively synchronous pattern with the thermal maximum at c. 7000 cal. yr BP, followed by a gradual cooling. The thermal maximum was reached c. 1000 years later in a diatom-based reconstruction (Korhola *et al.*, 2000). The reconstruction based on chironomids at Tsuolbmajavri shows an early Holocene thermal

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maximum followed by relatively cool period between 6000 and 2000 cal. yr BP (Korhola *et al.*, 2002). The reconstruction from tree-rings (Helama *et al.*, 2002) covers the last 7500 cal. yr BP. The general trend of this reconstruction is controversial compared with other proxies. According to the reconstructed midsummer temperature anomalies on the basis of tree-ring widths, the summer temperature on average increased gradually from 7500 cal. yr BP to the present (Helama *et al.*, 2002).

The expected global warming within the next 100 years compared with 1961–1990 climate normals is predicted to be 1.3–4.5°C (IPCC, 2001). Even if most of the warming effect at high latitudes is likely to occur during wintertime, a notable rise in summer temperatures is also predicted. Past positions of the pine forest line can be used for evaluating the response of coniferous forest to the changing climate.

This study aims to investigate the distribution changes of pine in space and time. Forest line and treeline are the main ecotone borders affected by these changes, and many different determinations and concepts have been presented for these lines (Hustich, 1966; Tuhkanen, 1999; Callaghan *et al.*, 2002). In this study, forest line is determined as a zone between a zone of closed forest stands and a zone of isolated trees or trees growing in small stands. Treeline is understood as the location of the outermost individual mature trees (as in Hustich, 1966).

The position of the present forest line of pine is tested against modern climate data. Subfossil pines, as well as evidence of the past presence of pine in dated lake sediments, are used to approximate the location of the former pine forest line at a given point in time. Past mean July temperatures are reconstructed on the basis of the assumption that mean July temperature at a given site at a given time has been at least as warm as it is at the present pine forest line. The most remote areas in Finland have not been studied for subfossil pines for logistical reasons. Since ‘absence of the evidence is not evidence of the absence’, it is not known if the pine limit has been situated even at higher latitudes and altitudes during the past. Therefore, the temperature reconstruction shows ‘at least as warm’ values. In this study we have used spatially detailed GIS-based data on the present forest line location (Sihvo, 2001, 2002; Juha Sihvo and Pertti Veijola, personal communication, 2003) and the model constructed predicts this location using climatic parameters (Mikkola and Virtanen, unpublished data, 2003). This is the first effort to model quantitatively the past

distribution patterns of pine in Finnish Lapland. The GIS approach was also used to generalize the present land-uplift rate for the study area.

Study area

The study area is in northernmost Finland and includes the present pine forest line region and areas above it (Figure 1). The Utsjoki–Inari region is characterized by gently sloping hills, typically varying between 200 and 300 m a.s.l., with the exception of some steep-sided river valleys (Seppälä and Rastas, 1980). The Enontekiö region is on the eastern flank of the Scandinavian mountain range, with the highest elevations over 1000 m a.s.l.

The bedrock of the western and southern parts of the Inari–Utsjoki region is part of the Lapland granulite complex and consists of gneisses and granitoids; the northeastern part belongs to the Inari complex and consists of gneisses, migmatites, foliated gabbro and granodiorite. Except for the northernmost part of the Enontekiö region, the rest of the study area is part of the Karelian Domain consisting of gneiss, granodiorite, quartz diorite, granite and quartz-feldspar schist, as well as of greenstones of the Central Lapland greenstone Belt. The bedrock in the most northern part of the Enontekiö region consists of Caledonidic schists and gneisses. Palaeozoic sedimentary rocks are found in the marginal zone of the Caledonides (Korsman *et al.*, 1997).

The dominating Quaternary deposit in the study area is till, but glaciofluvial and aeolian deposits are also found in minor quantities. The physico-chemical properties of the till depend on the source rock. Especially, the greenstone belt till differs from that in the granitoid complex (Koljonen, 1992). Till in the greenstone belt contains more fine-grained matrix having lower hydraulic conductivity than till in the felsic bedrock. Peatlands cover *c.* 17% of the study area, and they are especially common in the eastern parts of the Utsjoki–Inari area. Palsa mires are found in the peatlands in the mountain birch woodland between the present pine forest line and the barren areas.

The climate in the region is subarctic. Table 1 gives the climate normals from three local weather stations (see Figure 1 for locations). Mean January temperatures range from –14 to –16°C and mean July temperatures from 10.6 to 13.6°C. The

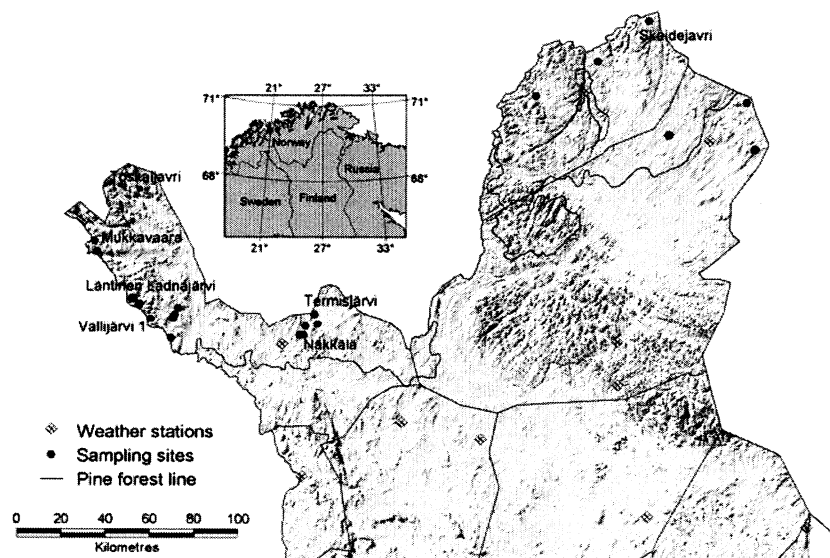


Figure 1 Topography of the study area and approximate position of the present pine forest line in northernmost Finland. Names of the sites that are discussed in the text are shown

Table 1 Climate normals (1961–1990) from three weather stations (for locations see Figure 1)

	1	2	3	4	5	6	7	8	9	10	11	12	annual
Kilpisjärvi <i>t</i> (°C)	−15	−13	−10	−4.8	1.5	7.5	10.6	9.1	4.4	−1.1	−7.8	−12.5	−2.6
Kilpisjärvi <i>p</i> (mm)	33	29	22	17	21	37	64	48	37	39	33	33	414
Ivalo <i>t</i> (°C)	−14	−13	−8.2	−2.2	4.4	10.8	13.6	11	5.9	−0.4	−7.3	−12.3	−1
Ivalo <i>p</i> (mm)	20	17	18	18	27	44	64	59	44	36	26	21	394
Kevo <i>t</i> (°C) ^a	−16	−14	−9.3	−3.1	3.22	9.53	12.7	10.2	5.3	−1.2	−8.4	−13.4	−2
Kevo <i>p</i> (mm) ^a	25	18	18	20	23	39	67	55	42	35	29	25	396

^aData from Kevo station is available from 1962.

annual precipitation is *c.* 400 mm, and *c.* 45% of the precipitation falls as snow.

The vegetation zones in the study region vary from slightly continental northern boreal to slightly oceanic and orohe-miarctic (Ahti *et al.*, 1968). The main tree species in Finnish Lapland are Scots pine, Norway spruce (*Picea abies*) and birch (*Betula pubescens*), especially mountain birch (*Betula pubescens* ssp. *czerepanovii* (syn. *B. pubescens* ssp. *tortuosa*)). Mountain birch forms both the altitudinal and latitudinal treeline. Above this a heath vegetation zone prevails, consisting of dwarf shrubs such as *Arctostaphylos alpina*, *Empetrum hermaphroditum*, *Phyllodoce caerulea*, *Vaccinium myrtillus* and *Betula nana*, with some lichens and mosses. Some locations are rocky and almost non-vegetated. The coniferous forest line is dominantly formed by pine, having an altitudinal limit of 380 m a.s.l. in the southern part of the study area and 100 m a.s.l. in the northernmost part, and is typically located 100–130 m below the mountain birch forest line. In some locations pine forms uniform stands, but more often these stands include a mixture of mountain birches (Seppälä and Rastas, 1980; Sihvo, 2002). South of the pine treeline, spruce reaches its latitudinal limit and roughly follows the northern border of the greenstone belt. In areas such as Pallastunturi, which also belongs to the greenstone belt, spruce forms the altitudinal conifer limit. Sutinen *et al.* (2002) claim that the distribution of the spruce in Finnish Lapland is not controlled only by climate, but also by soil properties. The distribution pattern of spruce is assumed to depend on soil properties, such as nutrients, pH and hydro-logical conductivity (see Sutinen *et al.*, 2002). Spruce is the dominant conifer species in the greenstone belt where mature stands of pine are rare. As the underlying bedrock in the Utsjoki–Inari region belongs to Granulite complex both above and below the present pine forest line, it can be assumed that the present position of the pine forest line is controlled mainly by climate.

Material and methods

All radiocarbon dates in the text are discussed as calibrated years before present (AD 1950) (cal. yr BP). The uncalibrated dates in previous studies were calibrated using the *Calib 4.1* program (Stuiver and Reimer, 1993). The ages of dendrochronologically dated subfossil trees are expressed as years before AD 1950. Radiocarbon dates are expressed at 100 yr accuracy and dendrochronological dates at 1 yr accuracy. Systematic sampling of pine megafossils in Finnish Lapland started in the early 1970s (Eronen, 1979). To date now, more than 3100 samples have been dated and assembled into a continuous pine chronology covering a total of 7522 years (Eronen *et al.*, 2002). In this study, only subfossils that are found above the present pine forest line are used. A total of 386 trees from 22 locations cover intervals 7469–2538 cal. yr BP and 1721–729 cal. yr BP. In addition to the pine megafossils, evidence

of stomata and pollen accumulation rates (PAR) were used from five lakes studied earlier (Eronen and Hyvärinen, 1982; Mäkelä *et al.*, 1994; Seppä, 1996; Seppä and Weckström, 1999; Seppä *et al.*, 2002). These lakes are situated above the present pine treeline. The pine record obtained from lake sediment covers an interval between 8700 and 3200 cal. yr BP. It has to be taken into account that the location of pine forest line during the Holocene is estimated on the basis of 27 sites only.

A model for the present pine forest line location in northern Finland was developed based on logistic regression, presented in more detail by Mikkola and Virtanen (unpublished data, 2003). A corresponding method has been effectively used in many studies to connect ecological phenomena to landscape- or climate-describing variables (Franklin, 1995), and it has been used in forest line location modelling in other areas (Virtanen *et al.*, 2004). Data sets used in modelling were digital elevation model data with a 25 m grid cell, climate data and the nature inventory GIS data base of the Finnish Forest and Park Service (Sihvo, 2001, 2002). The grid-based July mean temperature was produced using a model described by Ojansuu and Henttonen (1983). Measured temperature data (from the period 1961–1990) from the meteorological stations in the region (Figure 1) were spatially interpolated and smoothed by universal kriging (Cressie, 1991) to a 200 m grid covering the whole study area, taking into account the proximity of lakes, and the elevation effect (Ritari and Nivala, 1993). The nature inventory GIS data base consists of 237 000 land polygons including information on the field and tree layer properties, and covers all land areas owned by the state in northernmost Finland. From the pine coverage data of this data set, we calculated our binary response variable (pine forests present or not) developing a model for the forest line defined as a zone between a zone of closed forest stands and a zone of isolated trees or trees growing in small stands.

Glacio-isostatic land uplift

After deglaciation, the study area experienced land uplift that has varied both spatially and temporally. The present uplift rates estimated by Ekman (1996) were spatially interpolated in GIS using the kriging method (Cressie, 1991). The estimated present uplift rates vary from 1.5 to 4.6 mm/yr (Table 2). To estimate temporal variation in land uplift, observations in the Pello-Rovaniemi area (Saarnisto, 1981) were used to derive an equation ($R^2 = 0.99$) for land uplift adjusted elevation $h_{(t=x)}$;

$$h_{(t=x)} = h_{(0)} - ax(0.0001x + 0.9828) \quad (1)$$

where $h_{(0)}$ is present elevation (m), a is the present uplift rate (m/yr) at a specific site and x is cal. yr BP. This equation can be used for dates later than 9400 cal. yr BP. There are two main factors that cause uncertainties in this equation; first, the lack of studies concerning temporal variation in land uplift from other areas than Pello-Rovaniemi in Finnish Lapland and second, the present uplift rates are only estimations. Therefore

Table 2 Sites that have been used in this study. Mean July temperature is derived from the model of Ojansuu and Henttonen (1983). Present land uplift rate is interpolated to the sites after Ekman (1996). All the sites are above the present pine treeline

Site	X	Y	Elevation (m a.s.l.)	Pine present last cal. yr BP	Pine present (first and last cal. yr BP)	Type of evidence	Reference	Mean July temperature (°C)	Present land uplift rate (mm/yr)
1 Toskajärvi	21 27 02 E	69 11 28 N	704	8300	4000	Stomata, pollen	Seppä <i>et al.</i> , 2002	9.5	3.5
2 Mukkavaara	21 00 00 E	69 54 26 N	535	7800	3800	pollen	Eronen and Hyvärinen, 1982	10.4	3.7
3 Ailakkavaaran lompolo	20 57 06 E	68 57 18 N	515	6001	4085	megafossil	Eronen and Zetterberg, 1996	10.5	3.9
4 Itäinen Ladnajarvi	21 30 01 E	68 42 46 N	487	4253	4144	megafossil	Eronen and Zetterberg, 1996	11.0	4.3
5 Tsuolbmajarvi	22 03 15 E	68 41 19 N	526	6900	5700	pollen	Seppä and Weckström, 1999	11.1	4.3
6 Läntinen Ladnajarvi	21 28 50 E	68 42 44 N	481	6290	3547	megafossil	Eronen and Zetterberg, 1996	11.1	4.3
7 Tsohkkajarvi	22 01 13 E	68 39 25 N	505	6822	4621	megafossil	Eronen and Zetterberg, 1996	11.2	4.4
8 Vallijärvi 1	21 34 34 E	68 41 11 N	465	4582	1315	megafossil	Eronen and Zetterberg, 1996	11.2	4.3
9 Pohjoinen Haukijärvi	21 59 51 E	68 38 50 N	475	7012	3769	megafossil	Eronen and Zetterberg, 1996	11.3	4.4
10 Guoppalampi	26 23 10 E	69 42 49 N	147	6955	6096	megafossil	Eronen and Zetterberg, 1996	11.4	2.1
11 Eteläinen Haukijärvi	21 59 59 E	68 38 18 N	465	5487	4044	megafossil	Eronen and Zetterberg, 1996	11.4	4.4
12 Vallijärvi 2	21 34 46 E	68 41 34 N	465	7399	2573	megafossil	Eronen, 1979	11.5	4.3
13 Pätkikkä	21 43 50 E	68 37 45 N	400	5562	2630	megafossil	Eronen, 1979	11.6	4.4
14 Termisjärvi	23 43 03 E	68 42 04 N	440	1373	752	megafossil	Eronen, 1979	11.6	4.4
15 Lujuvuoli 220	29 09 32 E	69 27 46 N	220	4693	3525	megafossil	Eronen and Zetterberg, 1996	11.7	2.2
16 Jierstjärvi	23 45 56 E	68 39 13 N	465	7400	3200	pollen	Mäkelä <i>et al.</i> , 1994	11.8	4.5
17 Puollimvarinlompolo	29 04 46 E	69 40 22 N	160	6889	5947	megafossil	Eronen and Zetterberg, 1996	11.8	1.9
18 Njargaväärijärvi	29 09 12 E	69 27 34 N	220	6946	3769	megafossil	Eronen and Zetterberg, 1996	11.8	2.2
19 Lujuvuoli 210	29 10 17 E	69 27 36 N	210	6835	3229	megafossil	Eronen and Zetterberg, 1996	11.8	2.2
20 Kelotjärven suo	21 59 51 E	68 32 54 N	375	4484	2899	megafossil	Eronen and Zetterberg, 1996	12.0	4.6
21 Hatulompolo	23 37 04 E	68 38 37 N	385	7469	1294	megafossil	Eronen and Zetterberg, 1996	12.0	4.5
22 Skaidejärvi	27 50 48 E	70 03 06 N	182	8700	3400	pollen	Seppä, 1996	12.1	1.5
23 Näkkälä 3	23 36 06 E	68 36 10 N	390	2995	761	megafossil	Eronen, 1979	12.1	4.6
24 Näkkälä 1	23 33 10 E	68 36 07 N	370	3370	729	megafossil	Eronen, 1979	12.2	4.6
25 Selkojärvi B	28 04 56 E	69 32 12 N	208	7362	1275	megafossil	Eronen and Zetterberg, 1996	12.2	2.2
26 Selkojärvi C	28 04 00 E	69 32 02 N	208	7411	3769	megafossil	Eronen and Zetterberg, 1996	12.2	2.2
27 Selkojärvi D	28 04 10 E	69 32 09 N	208	7365	3961	megafossil	Eronen and Zetterberg, 1996	12.2	2.2

this equation gives only a suggestive estimate of land uplift during the Holocene.

The reconstructions of the mean July temperature and the past pine forest line

According to Mikkola and Virtanen (unpublished data, 2003), the present pine forest line follows, on average, the $+12.2^{\circ}\text{C}$ mean July temperature isohel, and 90% of the predicted forest line locations were within the range $11.6\text{--}12.8^{\circ}\text{C}$. July temperature explained 47% of the spatial variation in pine forest line location. The mean July temperature reconstruction is based on the assumption that during the past the pine forest line has had a similar response to temperature as it has today. That is, during the time when pine has been present at a given site, mean July temperature has been at least as high as it is at the present forest line. The second assumption is that the past forest line has been in balance with temperature.

For the July mean temperature reconstruction, only sites that have a lower estimated mean July temperature than at the present pine forest line (12.2°C) were used, a total of 385 pine megafossil samples from 22 sites and lake sediment record from five sites (Table 2). The reconstructions were performed in the following order. First, the difference between the present mean July temperatures of the sites and 12.2°C was calculated. Second, an adjusted elevation was calculated on the basis of Equation (1) for the site that at the given time had the highest temperature difference. Next, the present mean July temperature was calculated with the climate model for sites with adjusted elevation (Ojansuu and Henttonen, 1983). Finally, the temperature anomaly from the present was estimated on the basis of the difference between 12.2°C and the site temperature with adjusted elevation. The past distribution of pine was predicted on the basis of the forest line–temperature model (Mikkola and Virtanen, unpublished data, 2003) using the reconstructed temperature anomalies. The past distribution area was calculated from the land area, ignoring the water bodies, but including for example mire areas.

Results

The majority (82%) of the subfossil pines are dated to before 4000 cal. yr BP. An abrupt fall in sample size occurs at *c.* 4000

cal. yr BP (Figure 2). After this fall a short gap in regeneration within sampled trees occurs. Between 2538 and 1721 cal. yr BP no subfossil pines above the present pine forest line are dated. There is a late-Holocene sample size maximum around 1000 cal. yr BP. The last dated tree ring in subfossil pines above the present pine forest line is from 729 cal. yr BP (AD 1221). The number of sites that indicate a wider distribution of pine is highest (> 20) before 4000 cal. yr BP. Between 4000 and 2500 cal. yr BP the record contains ten sites and between 1700 and 700 cal. yr BP six sites.

Figure 3 shows the time distribution of the pine presence according to the present mean July temperature difference between sites and the present pine forest line (12.2°C). Only sites that have a lower modelled mean July temperature than 12.2°C have been included, 251 subfossil samples from 18 sites and lake sediment record from five sites. The pine record from Skaidejavri starts at 8700 cal. yr BP. The site is, however, situated so close to the present pine treeline that, adjusting for glacio-isostatic land uplift, modelled present temperature for the site is more than 12.2°C . Lake Toskaljavri has the highest temperature anomaly (2.7°C). Pollen and stomata data (Seppä *et al.*, 2002) suggest pine presence at least as scattered trees at the site between 8300 and 4000 cal. yr BP. The land uplift adjusted elevation of the site is 651 m a.s.l. (8300 cal. yr BP) and 685 m a.s.l. (4000 cal. yr BP). Modelled present temperatures for the site with adjusted elevation are 9.7°C (651 m a.s.l.) and 9.6°C (685 m a.s.l.). The Mukkavaara record continues until 3800 cal. yr BP. The modelled present mean July temperature with an adjusted elevation is 10.3°C . The record from Läntinen Ladnajärvi continues until 3550 cal. yr BP. The modelled mean July temperature with an adjusted elevation (3550 cal. yr BP) is 11.2°C . Vallijärvi 1 record continues until 1315 cal. yr BP. However, there is a gap in the record between 2641 and 1721 cal. yr BP. The land uplift adjusted temperatures show 11.3°C for 2650 cal. yr BP and for 1350 cal. yr BP. The last period in the Vallijärvi 1 record is based only on a single tree. The Termisjärvi record covers the period 1373–752 cal. yr BP. The modelled temperature is 11.7°C . Since the Vallijärvi 1 record during this period is for only one tree, reliable approximation of shift in mean July temperatures cannot be based on the Vallijärvi 1 record. The subfossil record terminates almost simultaneously at the three sites at *c.* 750 cal. yr BP. Figure 4a shows the

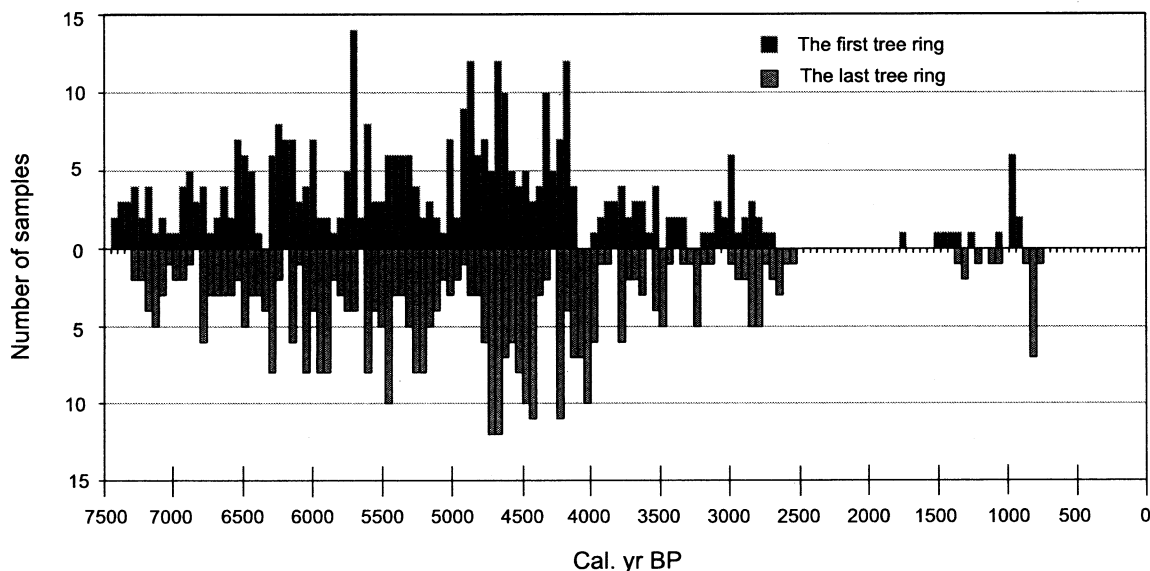


Figure 2 The time distribution of 385 subfossil pine samples in 22 sites above the present pine forest line of the first and the last dated tree rings. Sample size is that for a 50-yr non-overlapping period

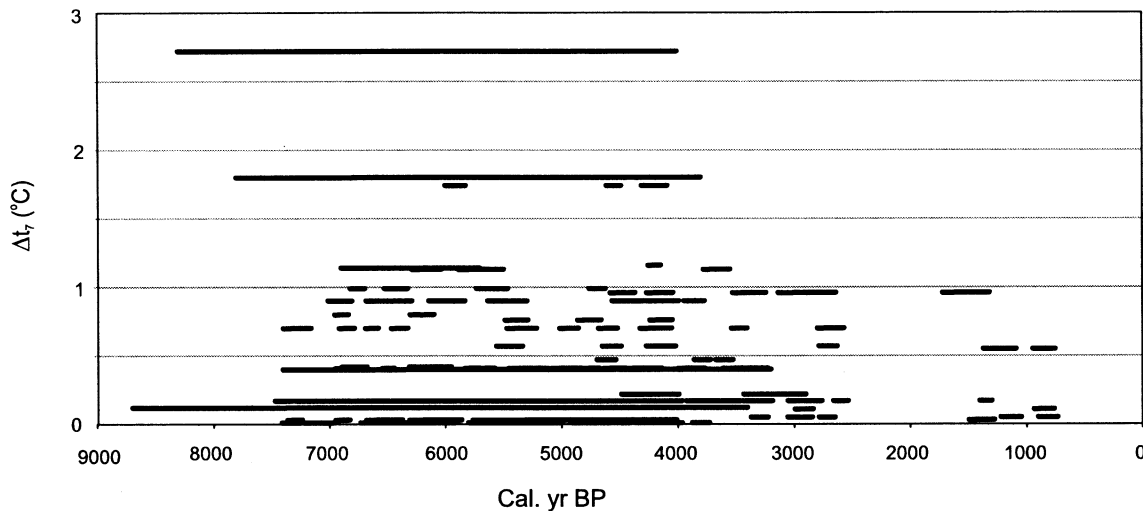


Figure 3 The time distribution of the pine presence according to the present mean July temperature difference between sites and present pine forest line (12.2°C)

reconstructed minimum shift in mean July temperatures, with elevation adjusted for land uplift, between 8300 cal. yr BP and the present. The record indicates that between 8300 and 4000 cal. yr BP the shift in mean July temperatures must have been at least +2.5–2.6°C to allow the pine forest line to reach Lake Toskaljavri. Between 4000 and 2650 cal. yr BP, the record suggests *c.* +1°C shift in mean July temperatures and *c.* +0.5°C shift at 1000 cal. yr BP compared to present.

Figure 5 shows the reconstructed past distribution of pine. Three points in time were selected: (1) 6000 cal. yr BP to estimate the situation during the maximum distribution of pine, (2) 3000 cal. yr BP to reflect the gradual withdrawal of the pine and (3) 1000 cal. yr BP to reflect the situation during the 'Mediaeval Warm Period'. According to the reconstruction, pine distribution was *c.* 13 000 km² more extensive during the Holocene climate optimum (6000 cal. yr BP) compared with the present distribution. According to our model, pine was absent only from the highest peaks in the Enontekiö region. At 3000 cal. yr BP, our model shows withdrawal of pine, especially in the mountainous Enontekiö region and the highest hills in the Utsjoki region. The distribution area of pine shows 10 500 km² more extensive pine distribution compared with the present one. The modelled distribution area of pine during the 'Mediaeval Warm Period' (1000 cal. yr BP) is still 7200 km² more extensive than it is at present.

Discussion

Since the location of the present pine forest line is determined mainly by the mean July temperature (Mikkola and Virtanen, unpublished data, 2003), it is assumed that during the Holocene the mean July temperature at the past pine forest line has been same as today. However, in the past other factors (eg, snow depth, length of the growing season, solar radiation and soil humidity) may have played a role (see Veijola, 1998a). Moreover, under the conditions of changing climate, the present forest line can be out of phase, ie, mature pine forest may not have reached its full extent allowed by climate factors. Forest cuttings may have also had some effect on present pine forest lines in some regions (Veijola, 1998b). The mean July temperatures used in this study (AD 1961–1990) are slightly lower when compared with a longer timespan (AD 1908–1990).

8300–4000 cal. yr BP

The present data suggest that the maximum extent of the pine occurred between *c.* 8300 and 4000 cal. yr BP in Finnish Lapland. During that time, pine had probably occupied all suitable soils (excluding, eg, steep rocky slopes and wetlands) except the highest peaks in the Enontekiö region. Studies focusing on the regions located beyond the present pine forest line are mainly concentrated in the Enontekiö region. In pollen- and stomata-based studies the pine migration to Finnish Lapland has been detected to have occurred *c.* 9000–8000 cal. yr BP (eg, Hyvärinen, 1975; Seppä, 1996). However, the record of subfossil pines that have been preserved in shallow lakes does not reach further back than 7469 cal. yr BP. One explanation for the lack of early subfossil pines in Finnish Lapland is the inferred lowering of the water-table after the very beginning of the Holocene (Hyvärinen and Alhonen, 1994; Sarmaja-Korjonen and Hyvärinen, 1999; Eronen *et al.*, 1999; Väiliranta *et al.*, 2005). As a consequence of this, shorelines withdrew and pines that grew and died near the shores did not have anoxic conditions that would enable the dead pines to be preserved for thousands of years.

The results are well in accordance with the studies from adjacent areas in the Kola Peninsula and northern Sweden. The pollen-based evidence from the Kola Peninsula (Solovieva and Jones, 2002) suggests the maximum extent of pine *c.* 8000–4200 cal. yr BP. Combined pollen and stomata evidence indicate pine presence beyond the present pine forest line between 9000 and 2800 cal. yr BP (Gervais *et al.*, 2002). Pollen accumulation rates, however, indicate that the maximum pine frequency was before *c.* 6800 cal. yr BP, after which the density of pine forest in the Kola Peninsula decreased until 2500 cal. yr BP when the present pine distribution was established (Gervais *et al.*, 2002). Subfossil pines found from the lakes beyond the present pine treeline in the Kola Peninsula indicate a more extensive distribution pattern of pine at *c.* 7500–3700 cal. yr BP and *c.* 1300 cal. yr BP onwards (MacDonald *et al.*, 2000a; Hiller *et al.*, 2001). Evidence from the Central Murman Coast indicates pine presence between 8000 and 6000 cal. yr BP (Snyder *et al.*, 2000). Studies from the Abisko area, northernmost Sweden, suggest pine presence above its current distribution as early as 9500–9100 cal. yr BP (Kullman, 1999) and 8500 cal. yr BP (Barnekow, 2000), but according to the pollen accumulation rates and plant macrofossil evidence it took almost 2000 years

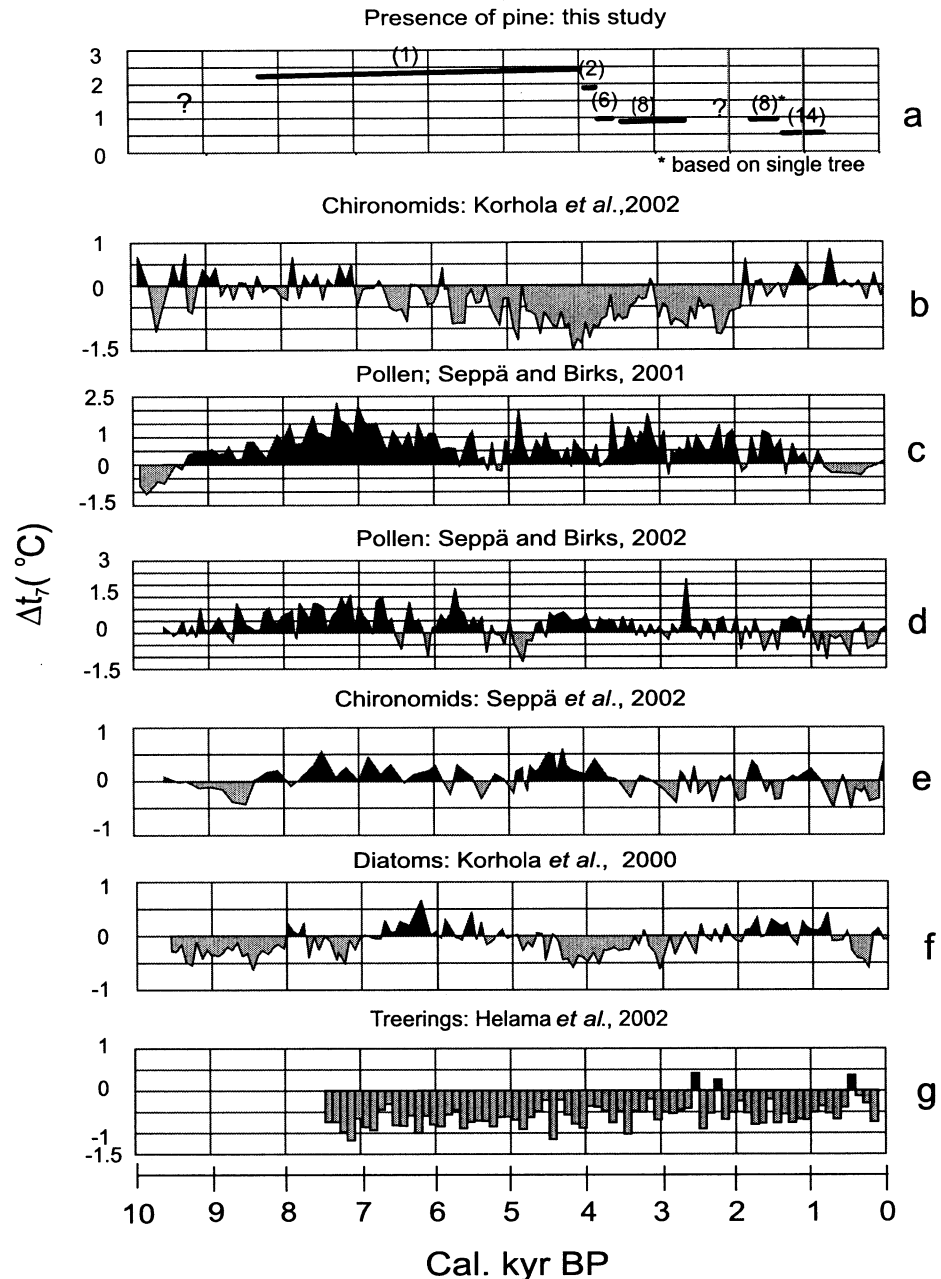


Figure 4 The mean July temperature anomalies from present in the reconstructions from Finnish Lapland. Reconstruction a shows minimum shift in mean July temperatures between 8300 cal. yr BP and present based on this study. Reconstructions from lake sediments (b, c, d, e and f) show deviations from the mean of three uppermost samples. In reconstruction g non-overlapping 100-yr mean deviations from the twentieth century are shown. Reconstructions b and c are from Tsuolbmajavri and d, e and f from Toskaljavri. Reconstructions a, b, c, d, e and f are elevation adjusted for land uplift. Numbers in parentheses in reconstruction a refer to the site number in Table 2

before a phase of closed forest was achieved (Barnekow, 2000). In summary, it seems evident that pine distribution and density in northern Fennoscandia was at its maximum prior to 6000 cal. yr BP.

The temperature reconstruction suggests that the mean July temperature has been at least 2.6°C higher than at present to allow the past location of the pine forest line. This is somewhat higher than results from pollen-based reconstructions suggest (1.4–1.7°C) (Figure 4c, d; Seppä and Birks, 2001, 2002). Reconstructed temperatures from other proxies suggest the Holocene thermal maximum *c.* 7000–6000 cal. yr BP (Figure 4; Korhola *et al.*, 2000, 2002; Seppä and Birks, 2001, 2002; Seppä *et al.*, 2002). Since our reconstruction between 8000 and 4000 cal. yr BP is based on only one location (Lake Toskaljavri), the temporal variations during this time cannot

be determined with this method. Estimates from the Abisko area, Sweden, show 1.5–2°C higher summer temperatures prior to 4500 cal. yr BP, having an optimum at *c.* 6500 cal. yr BP (Barnekow, 2000). Summer temperature reconstructions for the European Russian Arctic show from 2 up to 7°C higher temperatures during the early Holocene compared with the present (Kremenetski *et al.*, 1998; MacDonald *et al.*, 2000b; Kultti *et al.*, 2003, 2004).

4000–1850 cal. yr BP

On the basis of pollen analysis, the withdrawal of the pine forest in northern Finland has been interpreted to have started *c.* 6000 cal. yr BP (Hyvärinen, 1975, 1976; Seppä, 1996), continuing until 3300–2600 cal. yr BP (Hyvärinen, 1975). The altitudinal retreat of the upper limit of pine in the Abisko area,

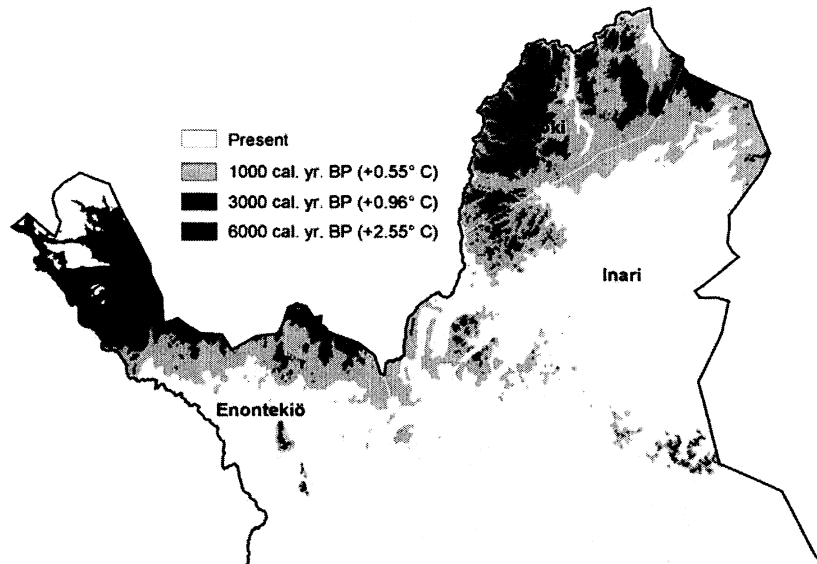


Figure 5 The modelled distribution of pine during maximum extent of pine (6000 cal. yr BP), during gradual withdrawal of pine (3000 cal. yr BP) and during the 'Mediaeval Warm Period' (1000 cal. yr BP) are indicated

northern Sweden, has been found to occur at different elevations at 5200, 4500 and 3400 cal. yr BP (Barnekow, 1999). The decline of the pine forest from above its present distribution area in the Kola Peninsula has been found to occur between 5700 and 2500 cal. yr BP (Kremenetski *et al.*, 1997; Gervais *et al.*, 2002; Boettger *et al.*, 2003). After 4000 cal. yr BP, a sharp decrease in subfossil pine sample frequency and site frequency might reflect an abrupt change in the growing conditions of pine, forced by climate. However, the divergence in the reconstructed beginning dates of withdrawal of pine forest between different sites and regions suggests that climate cooling in the mid Holocene has been gradual rather than abrupt.

No observations, neither in subfossil nor pollen and stomata evidence, on a wider distribution of pine compared with present in Finnish Lapland exist between 2537 and 1721 cal. yr BP. There are three main explanations for this: (1) pine did not grow beyond the present forest line, (2) subfossil pines have not been preserved, (3) these subfossils have not been found. Since 'absence of evidence is not evidence of the absence', we do not present any reconstructions of temperature or pine forest line for this period. Nevertheless, there is extensive evidence for a major climatic change during the first millennia BC (Eronen *et al.*, 1999; Oksanen, 2002; Lücke *et al.*, 2003; Tiljander *et al.*, 2003; Kultti *et al.*, 2004). Generally, climatic interpretations in northern areas show wet and cold conditions.

The most troublesome period within the pine chronology from northern Finland was the gap a few hundred years before 2000 cal. yr BP (Eronen *et al.*, 2002). After four years' intensive survey, subfossil pines that bridged this gap were found in lakes in present forested areas. Eronen *et al.* (2002) suggested that the abrupt fall in tree growth detected in dendrochronological studies at 2280 cal. yr BP is due to a rise in the lake levels caused by increased effective humidity in the late Holocene. If a continuous increase in humidity is assumed, advantageous conditions for the preservation of trees could be expected. However, good preservation of trees was not observed even further south from the present pine forest line. On the other hand, if there had been notable fluctuations in lake levels during that time, it could explain the absence of trees.

An analogous lack of subfossil pines is observed from the Kola Peninsula at 3700–1300 cal. yr BP (MacDonald *et al.*,

2000a; Hiller *et al.*, 2001). This supports (but does not prove) the assumption that pine did not grow, or was few in number, above the present pine forest line zone during this period. Permafrost aggradation in northern Finland indicating a cold environment has been observed in the palsamires at c. 2500 cal. yr BP (P.O. Oksanen, personal communication, 2003). Oksanen (2002) has interpreted from the previously studied palsas the permafrost aggradation to have occurred at c. 2100 cal. yr BP in Faerdesmyra, Norway (Vorren, 1972), and roughly at the same time (late sub-Boreal) appearance of permafrost in the Kola Peninsula (P'yavchenko, 1955).

Permafrost aggradation has also been observed in NE European Russia between 3400 and 1800 cal. yr BP (Oksanen *et al.*, 2001). A varve record from Lake Korttajärvi in central Finland shows a strong abrupt anomaly in mineral material accumulation, indicating severe climate conditions at c. 2850 cal. yr BP, which is simultaneous with observed decrease in *Picea* and deciduous tree pollen percentages from the same lake (Tiljander *et al.*, 2003). In the Korttajärvi record the climate during the first millennium BC has been interpreted to alternate cyclically (Tiljander *et al.*, 2003). Taking into account the evidence from the other proxies from Finland and the adjacent Kola Peninsula, it is presumable that the lack of evidence of subfossil pines beyond the present pine forest line zone during this period is because of either colder climate or a significant variability in lake levels or interaction of both.

1850 cal. yr BP to present

Megafossils of pine from between 1850 and 720 cal. yr BP, have been found from six sites beyond the present pine forest line. The number of samples has a distinct maximum between 1000 and 770 cal. yr BP in Finnish Lapland. The record suggests 0.55°C higher mean July temperatures than at present. At the same time, presence of pine has been detected c. 100 m above the current pine limit in Sweden (Kullman, 1998) and 100–140 m above in the Kola Peninsula (Hiller *et al.*, 2001). The same pattern at the upper larch (*Larix sibirica*) timberline on the Eastern side of the Ural Mountains has also been found; from c. 1000 cal. yr BP to c. 600 cal. yr BP numerous megafossils have been found from above the present tree limit (Shiyatov, 1993). Assuming a lapse rate 0.6°C per 100 m, these finds correspond with a shift of +0.6–0.8°C in temperatures.

The conifer limit during the 'Mediaeval Warm Period' appears to have been well above the present conifer limit in extensive areas in Fennoscandia and Russia. This suggests that the climate during the 'Mediaeval Warm Period' was even warmer than during the twentieth century in northern Fennoscandia. Most of the quantitative reconstructions from Finnish Lapland (Figure 4) show warmer than at present at *c.* 1000 years ago (Korhola *et al.*, 2000, 2002; Seppä and Birks, 2001, 2002, Seppä *et al.*, 2002). Only reconstruction made from tree-ring widths suggests colder than at present mean July temperature (Helama *et al.*, 2002).

The 'Little Ice Age' can be seen in our data as a gap between the last subfossil samples beyond the present pine treeline and the new young pine stands above the present mature forest line. An absence of observations indicates that the pine forest line situated either close to the present treeline or, in some cases, south of its present position. Similar depression of treeline can be seen in the Kola Peninsula (Hiller *et al.*, 2001), Northern Scandinavia (Kullman, 2001) and the Ural Mountains (Shiyatov, 1993).

An upward migration of pine forest line during the twentieth century, especially in the 1920s in Finnish Lapland, was observed as early as in the 1950s (Hustich, 1958). Currently, the pine treeline belt is in some cases formed by young pines that typically are less than 100 years old. The recent advance of the pine treeline (especially altitudinal) is a few tens of metres above the altitude of the mature pine treeline. The same phenomenon is also observed in the southern Scandes of Sweden (Kullman, 2001) and in the Ural Mountains (Shiyatov, 1993).

Several studies consider the twentieth century as the warmest in the Northern Hemisphere during the last millennium (Mann *et al.*, 1999; Crowley and Lowery, 2000) or the last two millennia (Briffa, 2000). However, the modelled pine distribution area in Finnish Lapland during the 'Mediaeval Warm Period' is *c.* 7200 km² more extensive compared with the present, suggesting that the mean July temperatures were higher during the 'Mediaeval Warm Period' than at present. Nevertheless, it has to be pointed out that the migration of the forest belt might show a significant lag in response to warming or cooling climate and, therefore, the current pine forest line might not be in equilibrium with temperatures. In the future, even a small shift (*c.* 0.5°C) in mean July temperatures might have a noteworthy effect on forest distribution, which in turn could have a significant feedback effect on the expected climate warming (Foley *et al.*, 1994; Betts, 2000).

Conclusions

Past shifts in pine forest line position in Finnish Lapland and mean July temperatures were reconstructed. The reconstruction is based on past records of pine presence above the present pine forest line, and on the model derived from the present pine forest line and mean July temperatures (1961–1990).

The results suggest that probably the maximum encroachment of pine was into all areas in northern Finland with suitable soils, except for the highest peaks in the Enontekiö region. Between *c.* 8000 and 4000 cal. yr BP pines were growing at 350–400 m higher altitudes than at present and the shift in mean July temperatures compared with 1961–1990 climate normals was +2.5–+2.6°C. The lack of evidence for a wider distribution of pine between 2537 and 1721 cal. yr BP might reflect a cold period or a significant variability in lake levels or interaction of both. During the 'Mediaeval Warm Period' the distribution area of pine was 7200 km² more extensive than at

present, and pines were growing at 40–80 m higher altitudes. For this period, the mean July temperature reconstruction shows +0.55°C shift compared with the present.

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