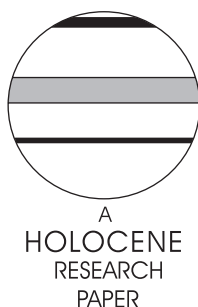


Radiocarbon-dated peat and wood remains from the Finnish Subarctic: evidence of treeline and landscape history

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Abstract: Seven peat and 40 dead wood remains (mountain birch) were sampled within and above the present treeline ecotone on two mountains (Rodjanoaivi, Koahppeloarvi/Staloskaidi) along the Tenojoki in northernmost Finnish Lapland. The oldest peat samples ('summit peats') date back to about 2000 yr BP. They accumulated during cool and increasingly humid climatic conditions. The other peat samples taken from wind-eroded peat remains on convex topography 60–100 m above the present tree limit are about 700–1300 years old. These peat layers developed during a phase of increasing *Sphagnum* peat formation. An eroded peat-covered Podzol that had developed under former tree stands with dwarfshrub vegetation in the understorey also reflects this climatic change. The oldest birch wood samples date from the same period. These and the many younger samples are evidence for a general treeline decline since the Holocene climatic optimum until present. As a result of the decline of the upper forest stands, the alpine zone has extended downslope and wind erosion has increased considerably in the former and present treeline ecotone, removing most of the peaty layers and top soils from wind-exposed topography. Whilst the cooling climate was the main factor triggering treeline retreat, episodic mass-outbreaks of the autumnal moth (*Epirrita autumnata*), particularly when coincident with cold summers, must also be taken into consideration as a factor that enhanced or accelerated treeline decline during this period. As is evidenced by the wood samples, forest decline continued into modern times when overgrazing by reindeer (*Rangifer tarandus*) became an additional factor enhancing wind erosion and affecting the regeneration of birch in the present treeline ecotone.

Key words: Mountain birch, treeline, climate change, 'Little Ice Age', autumnal moth, reindeer, wind erosion, late Holocene, Subarctic, Finland.

Introduction

The general climate and treeline history of northern Fennoscandia has been well documented using pollen analysis tree-ring analysis and radiocarbon-dated peat and wooden remains (eg, Eronen, 1979; Kullman, 1987a,b, 1990, 2005a and b, and references therein; Eronen and Zetterberg, 1996; Eronen *et al.*, 1999a,b; Barnekow, 2000; Luoto and Seppälä, 2000). In northern Fennoscandia, the treeline declined since the post-glacial thermal optimum (4000–5000 BP) because of a general cooling of the climate. Humidity generally increased from about 3000 to 2500 BP, as indicated by increased accumulation of *Sphagnum*-peat (sub-Atlantic period; Zetterberg *et al.*, 1994; Seppä, 1996; Eronen and Zetterberg, 1996; Eronen *et al.*,

1999a). Regional differences have become apparent, however, eg, in humidity trends (Eronen and Zetterberg, 1996).

Further data may allow greater regional and local differentiation of the phenomenon (see also Eronen and Zetterberg, 1996). During field research on treeline dynamics in the Finnish Subarctic (eg, Holtmeier, 1974, 2003; Holtmeier *et al.*, 2003, Holtmeier *et al.*, 2004; Holtmeier and Broll, 2005) peat and dead wood samples were obtained from the fells of Rodjanoaivi and Koahppeloarvi/Staloskaidi for radiocarbon-dating. The results of these analyses should broaden our knowledge on the effects of fluctuating climate on treeline and landscape history in the study area.

Study area

Rodjanoaivi (509 m a.s.l.) and Koahppeloarvi/Staloskaidi (419.6 m a.s.l.) are located in the granulite area of northern-

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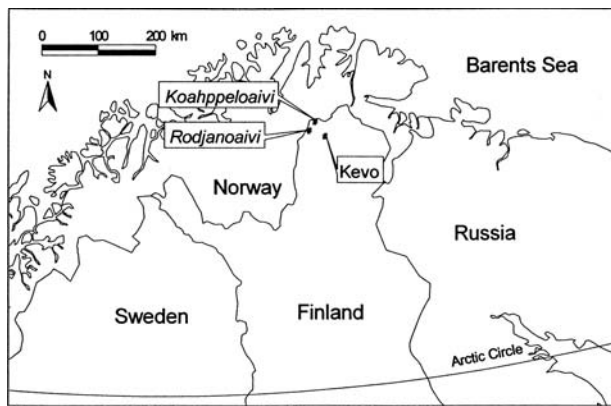


Figure 1 Location of the study area

most Finnish Lapland (northwestern Utsjoki, Figure 1). The crystalline bedrock (Korsman *et al.*, 1997) is covered for its most part by up to 3 m thick sandy-skeletal basal till, which became dissected by meltwaters and the present small tributaries of the Tenjoki (Tana river). The regional climate is subcontinental (Oksanen and Virtanen, 1995). The mountains are influenced by strong winds throughout the year, mainly from the west and north. Wind erosion is very common on the mountains above the closed mountain-birch forest (Holtmeier, 2003; Seppälä, 2004; Holtmeier *et al.*, 2004). Closed mountain birch forest ends at about 240 m 300 m a.s.l. Birch groves and solitary birches occur up to 360 m a.s.l., mainly in valleys, which provide shelter from the winds (Holtmeier *et al.*, 2003, 2004). Oligotrophic dwarfshrub-lichen heath (Haapasaaari, 1988) interspersed with exposed mineral soil is typical of the treeline ecotone and the alpine zone above. Remains of shallow peaty layers and low peaty hummocks (15–30 cm high), often containing more or less decomposed wood (mainly root stocks) widely occur in the treeline ecotone.

Method

The samples for radiocarbon-dating were taken from the residual, usually wind-eroded peaty layers, from rotten root-stocks and other dead wood usually overgrown by dwarfshrub-lichen vegetation and embedded in more or less decomposed organic matter. Altogether, seven peat samples and 40 dead birch wood remains were taken. The coordinates of the sampling sites are documented in Table 1.

Sampling depth varies, although most samples were taken at 10–30 cm below the surface close to the mineral substrate (sandy-skeletal basal till). All visible living material such as fine roots etc. was carefully removed to prevent contamination of the samples. Immediately after sampling, the samples were dried in a desiccator for three days at 50–60°C and were then air-dried for a further two weeks. Radiocarbon-dating of the samples was conducted by the Leipzig Institute for Applied Geosciences (Section 3: Geochronology and Isotope Hydrology) in Hannover, Germany.

Results

The ^{14}C age (years BP) and calibrated age (time interval BC/AD) of the peat and wood samples are listed in Table 1. In addition, Figure 2 gives the chronological order of the samples as indicated by their calibrated ages.

Peat samples

Three of the seven peat samples were taken at the upper treeless rims of wind-facing valley sides (Figure 3a). Three samples come from residual peaty layers on low ridges (Figure 3b). The peaty layers are shallow and wind-eroded as is evident from the typically downwind-advancing crescent-shaped scarps (Figure 4). Only relatively few remnants of the original lichen crust and dwarfshrub vegetation (mainly *Empetrum hermaphroditum* and espaliers of *Loiseleuria procumbens*) still exist. It is very likely that reindeer have destroyed the plant cover through grazing, trampling and also by wallowing. Consequently, the peaty layers became vulnerable to wind erosion. The ^{14}C age of these samples (Table 1: lab code 25196, 25160 and 25164) taken on Rodjanoarvi is 1210 ± 50 yr BP (cal. yr AD 725–855), 1175 ± 50 yr BP (cal. yr AD 780–940) and 680 ± 50 yr BP (cal. yr AD 1280–1385).

A so-called ‘summit peat’ or ‘peat cake’ (Luoto and Seppälä, 2000) has accumulated behind a rocky outcrop on top of Rodjanoarvi (Figure 3c). A dense mat (height 2–3 cm) of *Empetrum hermaphroditum* covers the peat. The peat has been dated to be 2055 ± 45 yr BP (cal. yr 100 BC–AD 4) old (cf. Table 1: lab code 24952). A second peat sample was 2005 ± 55 yr BP (cal. yr 85–65 BC) old (cf. Table 1: lab code 25197; see also Holtmeier *et al.*, 2004). These samples were taken right behind the leeward side of the rock at 40 cm depth just above the mineral substrate. A third sample from near the peat surface could not be dated because it was contaminated, very likely by fine roots of the dwarf-shrub cover.

On Staloskaidi (cf. Figure 1), a sample was taken from the base of a 15–30 cm deep peat layer on a low step crossing a shallow valley at about 300 m a.s.l. (Figure 3d). The peat covers a Podzol the top soil of which had become eroded or incorporated into the peat (Figure 3d and Figure 5). This sample was dated to be 960 ± 45 yr BP (cal. yr AD 1020–1155) old (cf. Figure 1, lab code 25185).

One peat sample taken from a shallow peaty layer at 10 cm depth on a small ridge at 324 m a.s.l. on the northeast-facing slope of Koahppeloarvi could not be exactly dated because of too high ^{14}C content (pMC > 100). Possibly it was contaminated by roots of the recent dwarfshrub vegetation. However, the calibrated age of a dead wood sample (cf. Table 1: lab code 25193) taken from this organic layer at the same depth and just 1 m aside the peat sampling site was 1695–1955.

Dead wood samples

Birch wood remains older than 200 years are very rare. One such piece taken on Rodjanoarvi at 395 m a.s.l. at 30 cm depth from a peaty hummock (30 cm high, reddish colour, slightly or moderately decomposed) covered with lichens and low *Empetrum hermaphroditum* (Figure 3e) has a radiocarbon age of 950 ± 60 yr BP (cal. yr AD 1020–1165, cf. Table 1, lab code 23565). Another one taken at 10 cm depth from a wind-eroded 20 cm thick peaty layer on a low ridge at about 400 m a.s.l. was 915 ± 55 yr BP (cal. yr AD 1035–1175, cf. Table 1, lab code 25163).

Two samples taken on Rodjanoarvi at about 362 m and 366 m a.s.l. were 555 ± 55 yr BP (cal. yr AD 1320–1430, cf. Table 1, lab code 22868) and 415 ± 55 yr BP old (cal. yr AD 1440–1615, cf. Table 1, lab code 22869). The older sample was taken at 10 cm depth from an almost completely rotten birch root stock on the eroded wind-facing side of a shallow Podzol at 362 m a.s.l. on wind-eroded convex topography (cf. Figure 3b). The younger sample was taken from root stock remains at the base of a 10 cm high peaty hummock at the upper rim of a valley side (cf. Figure 3a).

Table 1 ^{14}C age (BP) and calibrated time interval (BC/AD) of peat and dead wood samples

Sampling site	Lab code	Material	Coordinates	Altitude (m)	$\delta^{13}\text{C}$ age ‰	^{14}C age (yr BP)	Cal. time interval (yr BC/AD)
Rodjanoaivi	24951	Peat	60° 49' 31"/26° 24' 43"	509	-26.9	n.d.	-
Rodjanoaivi	24952	Peat	60° 49' 31"/26° 24' 43"	509	-26.9	2055 ± 45	100 BC-AD 4
Rodjanoaivi	25160	Peat	69° 50' 22"/26° 23' 56"	373	-27.3	1175 ± 50	AD 780-940
Rodjanoaivi	25164	Peat	69° 50' 27"/26° 24' 47"	390	-27.8	680 ± 50	AD 1280-1385
Stalokskaidi	25185	Peat	69° 55' 14"/26° 50' 30"	303	-29.1	960 ± 45	AD 1020-1155
Koahppeloaiivi	25194	Peat	69° 56' 30"/26° 48' 51"	324	-27.4	n.d.	-
Rodjanoaivi	25196	Peat	69° 50' 22"/26° 23' 16"	380	-27.9	1210 ± 50	AD 725-855
Rodjanoaivi	25197	Peat	69° 49' 31"/26° 24' 43"	509	-27.5	2005 ± 55	85 BC-AD 65
Rodjanoaivi	22868	Wood	69° 50' 31"/26° 24' 04"	362	-27.0	555 ± 55	AD 1320-1430
Rodjanoaivi	22869	Wood	69° 50' 29"/26° 24' 33"	366	-28.3	415 ± 55	AD 1440-1615
Rodjanoaivi	22870	Wood	69° 50' 31"/26° 4' 44"	373	-29.1	170 ± 45	AD 1665-1954
Rodjanoaivi	23565	Wood	69° 50' 27"/26° 25' 11"	395	-28.1	950 ± 60	AD 1020-1165
Rodjanoaivi	25161	Wood	69° 50' 21"/26° 23' 55"	361	-28.0	280 ± 45	AD 1520-1660
Rodjanoaivi	25162	Wood	69° 50' 23"/26° 23' 46"	359	-29.4	240 ± 45	AD 1525-1945
Rodjanoaivi	25163	Wood	69° 50' 19"/26° 24' 18"	407	-28.4	915 ± 55	AD 1035-1175
Rodjanoaivi	25165	Wood	69° 50' 30"/26° 24' 42"	383	-29.1	190 ± 45	AD 1655-1945
Stalokskaidi	25166	Wood	69° 55' 25"/26° 51' 59"	255	-31.1	70 ± 45	AD 1690-1955
Stalokskaidi	25167	Wood	69° 55' 25"/26° 51' 59"	255	-31.3	70 ± 45	AD 1690-1955
Stalokskaidi	25168	Wood	69° 55' 18"/26° 32' 04"	283	-29.4	n.d.	after AD 1950
Stalokskaidi	25169	Wood	69° 55' 16"/26° 52' 05"	289	-29.9	n.d.	after AD 1950
Stalokskaidi	25170	Wood	69° 55' 03"/26° 52' 01"	300	-28.4	n.d.	after AD 1950
Stalokskaidi	25171	Wood	69° 45' 58"/26° 51' 03"	315	-28.4	140 ± 80	AD 1670-1945
Stalokskaidi	25172	Wood	69° 55' 02"/26° 51' 23"	328	-30.1	140 ± 50	AD 1675-1945
Stalokskaidi	25173	Wood	69° 55' 03"/26° 51' 31"	330	-29.2	55 ± 50	AD 1690-1955
Stalokskaidi	25174	Wood	69° 55' 10"/26° 51' 51"	282	-30.8	155 ± 45	AD 1665-1945
Stalokskaidi	25175	Wood	69° 55' 01"/26° 50' 10"	355	-29.6	n.d.	after AD 1950
Stalokskaidi	25176	Wood	69° 54' 55"/26° 49' 54"	354	-28.5	60 ± 50	AD 1650-1955
Stalokskaidi	25177	Wood	69° 54' 54"/26° 49' 51"	358	-28.8	n.d.	AD 1650-1950 ^a
Stalokskaidi	25178	Wood	69° 54' 54"/26° 49' 48"	356	-30.0	n.d.	AD 1650-1950 ^a
Stalokskaidi	25179	Wood	69° 54' 57"/26° 49' 48"	352	-30.1	n.d.	AD 1650-950 ^a
Stalokskaidi	25180	Wood	69° 55' 01"/26° 49' 48"	345	-28.9	n.d.	AD 1650-950 ^a
Stalokskaidi	25181	Wood	69° 55' 01"/26° 49' 38"	348	-28.3	n.d.	after AD 1950
Stalokskaidi	25182	Wood	69° 55' 13"/26° 49' 39"	353	-28.9	235 ± 50	AD 1530-1945
Stalokskaidi	25183	Wood	69° 55' 14"/26° 49' 41"	349	-29.3	n.d.	after AD 1950
Stalokskaidi	25184	Wood	69° 55' 15"/26° 49' 42"	346	-28.9	n.d.	after AD 1950
Stalokskaidi	25186	Wood	69° 54' 52"/26° 47' 43"	364	-30.4	n.d.	after AD 1950
Juntekoaiivi	25187	Wood	69° 54' 52"/26° 47' 42"	3640	-28.3	150 ± 75	AD 1670-1945
Koahppeloaiivi	25188	Wood	69° 54' 56"/26° 47' 38"	380	-29.5	50 ± 45	AD 1650-1955
Koahppeloaiivi	25189	Wood	69° 56' 32"/26° 48' 59"	320	-29.6	n.d.	after AD 1950
Koahppeloaiivi	25190	Wood	69° 56' 32"/26° 49' 01"	319	-27.0	n.d.	after AD 1950
Koahppeloaiivi	25191	Wood	69° 58' 38"/26° 49' 20"	297	-29.8	60 ± 50	AD 1690-1955
Koahppeloaiivi	25192	Wood	69° 56' 32"/26° 40' 01"	322	-28.6	60 ± 45	AD 1695-1950
Koahppeloaiivi	25193	Wood	69° 56' 30"/26° 48' 52"	324	-28.2	60 ± 45	AD 1695-1955
Koahppeloaiivi	25195	Wood	69° 56' 30"/26° 48' 52"	325	-28.9	50 ± 50	AD 1695-1955
Stalokskaidi	25198	Wood	69° 55' 03"/26° 50' 59"	314	-28.7	n.d.	AD 1650-1950 ^a
Stalokskaidi	25199	Wood	69° 55' 21"/26° 52' 05"	264	-27.7	n.d.	AD 1650-1950 ^a
Stalokskaidi	25200	Wood	69° 54' 52"/26° 51' 43"	319	-27.9	160 ± 50	AD 1665-1945
Stalokskaidi	25201	Wood	69° 54' 54"/26° 51' 43"	315	-29.1	85 ± 45	AD 1690-1950

^apMC < 100, calibrated with 68% probability.

A couple of samples were between 200 yr and 300 yr old (280 ± 45 yr BP, 240 ± 45 yr BP, 235 ± 50 yr BP, 190 ± 45 yr BP; cf. Table 1, lab codes 25161, 25162, 25182, 25165). They can be assigned to the 'Little Ice Age' and the period following until the middle of the twentieth century. All of these samples were taken from slightly or moderately decomposed peaty layers on low ridges and at the upper rim of valley sides at 10 cm to 15 cm depth (cf. Figure 3a and 3b).

Although poorly preserved and partly at an advanced stage of decomposition 18 samples, mainly from Stalokskaidi and from Koahppeloaiivi, turned out to be too young for radiocarbon dating (^{14}C > 100 pMC; see Figure 2). Consequently a calibrated time interval could not be determined. Some were taken from snags and wood remains partly overgrown by dwarf shrubs and lichens. These trees died about 1950.

Discussion

The oldest peat samples taken from the 'summit peat' on Rodjanoaivi date back to the sub-Atlantic when, in addition to the cooling, humidity increased throughout northernmost Fennoscandia (Zetterberg *et al.*, 1994; Seppä, 1996; Eronen and Zetterberg, 1996; Eronen *et al.*, 1999a) and favoured the development of bogs (mires). Luoto and Seppälä (2000) consider the 'summit peats' occurring on many mountain tops in northern Finnish Lapland to be remains of blanket bogs in *statu nascendi* ('embryonic blanket mires', Luoto and Seppälä, 2000) at the easternmost (continental) distribution limit of this type of bog. The 'summit peat' on Rodjanoaivi (Figure 3c, about 2000 yr old) would appear to conform with this hypothesis. Under present climatic conditions 10 cm of

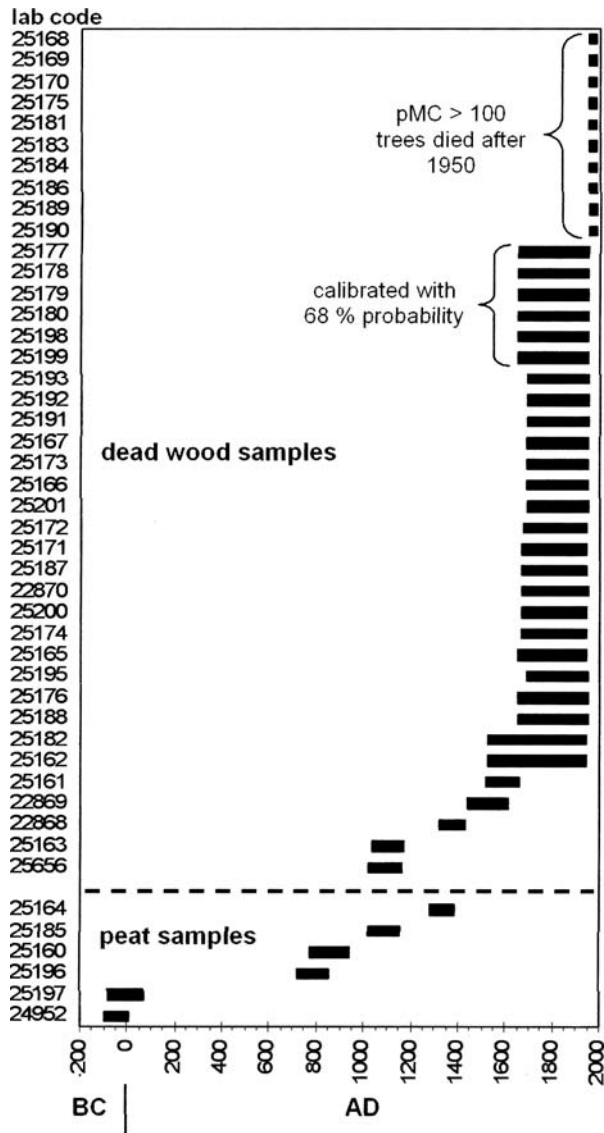


Figure 2 Chronological order of peat and dead wood samples (mountain birch) as indicated by their calibrated age

peat may accumulate within less than 50 years (Van Vliet-Lanoë and Seppälä, 2002). Thus, the peat sample from Koahppeloaiivi (lab code 25194, Table 1) that could not be dated because of too high ¹⁴C content accumulated after 1950. Assuming a similar peat accumulation rate for the ‘summit peat’ in question, the upper peat layers accumulated about 200 years later than the basal peat layer, gradual compaction and possible losses by wind erosion not included. The ‘summit peat’ could therefore persist on the wind-swept mountain top until present because of its leeward position and the dense crowberry mat, which has protected it from the action of the wind.

If not a result of complete decomposition of any possible evidence, the lack of wood remains in the ‘summit peat’ (see also Luoto and Seppälä, 2000) and on top of Rodjanoaiivi may indicate treelessness of the mountain top area since the beginning of the sub-Atlantic at least. Missing relics of ancient forest soils also appear to support this hypothesis. Moreover, periglacial patterned ground, which is common on almost level or gently sloping parts of the upper mountain slope, and which must have developed during treeless conditions, corroborates this assumption.

The generally harsh climatic conditions 2500–2000 years ago that caused severe disturbance to pine (*Pinus sylvestris*) at

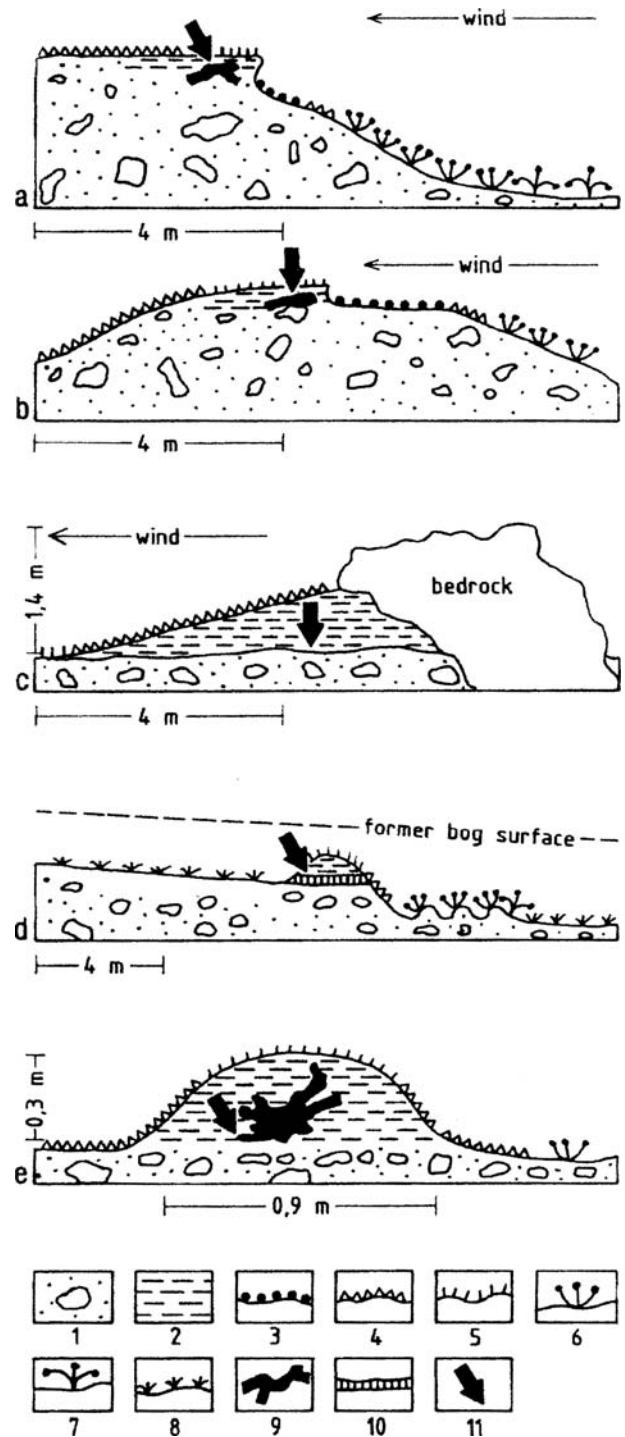


Figure 3 Location of the peat and/or dead wood samples. (a) Wind-exposed upper rim of valley sides; (b) wind-exposed convex topography; (c) ‘summit peat’ (Rodjanoaiivi); (d) peat-covered step (ridge) crossing a shallow valley (Staloskaidi); (e) peaty hummock. 1, basal till; 2, peat; 3, exposed mineral soil; 4, *Empetrum*-heath; 5, lichens; 6, dwarf birch; 7, willow shrub; 8 grass bog; 9, wood remains; 10, Podzol; 11, sampling point

the forest limit (Eronen *et al.*, 1999a,b; see also Kullman, 1987b, 1995; Dahl and Nesje, 1996) presumably affected also mountain birch, particularly in the treeline ecotone. On the other hand, increase of humidity due to the generally changing climate might have become exacerbated by the treeline decline because water loss by transpiration would have been considerably reduced. Thus, the decay of the upper forest stands might have indeed favoured peat formation. On the other hand, when the birch stands declined, less snow accumulated in the former



Figure 4 Downwind (to the left) advancing, crescent-like wind scarps eroded in a shallow peaty layer on slightly convex topography (cf. Figure 3b), northwest-facing slope of Rodjanoaivi at 377 m a.s.l. Photo by F.-K. Holtmeier, 25 August 2003

forested areas (cf. Holtmeier, 2005a). It remains an open question whether reduced transpiration would have compensated for decreased meltwater supply.

The younger eroded peaty layers (about 700–1300 yr BP, cf. Figure 2) on wind-exposed topography (cf. Figures 3a, 3b and 4) also accumulated during cool and wet conditions. This period largely corresponds to the period of increasing *Sphagnum*-peat formation, which began about 1000 yr BP (cf. Van Vliet-Lanoë and Seppälä, 2002) and was followed by the ‘Little Ice Age’. The deterioration of the climate in the twelfth century can be considered as the beginning of this cold period (Grove, 1988; Grudd *et al.*, 2002). However, opinions seem to be divided concerning the ‘precise’ timing of the ‘Little Ice Age’. Some authors use the data *c.* AD 1300 to 1900 (eg. Käyhkö *et al.*, 1999; Kullman, 1989b), whilst others use *c.* AD 1500 to 1900 (eg. 1859; Lamb, 1982; Grove, 1988; Kullman, 1990; Bradley and Jones, 1993; Matthews *et al.*, 1993) or even AD 1600 to 1900 (Rosen *et al.*, 2002). In northern Europe, temperature was 1–2°C below the twentieth-century temperature level (Matthews, 1977; Matthews and Caseldine, 1987; Kullman, 1987a, 1990). However, the ‘Little Ice Age’ was not a continuous cold period but interrupted by brief warm intervals (eg. 1541–150; Briffa *et al.*, 1990, 1995, 1999, 2001; Helama *et al.*, 2002). Moreover, the timing of the ‘Little Ice Age’ varies

geographically (Bradley and Jones, 1993; Intergovernmental Panel on Climate Change, 2001).

The peat (960±45 yr BP, cf. Table 1, lab code 25185) on the low step crossing a shallow valley on Staloskaidi accumulated during this cool period, for example (cf. Figure 3d and Figure 5). In contrast, the Podzol underneath this peat must have formed whilst good drainage conditions existed (permeable substrate, convex site), before the peat accumulated. Very likely, mountain birch stands with dwarfshrub undergrowth covered this site at that time. At least there was no evidence of pine remains in the study area that could be attributed to this period. If pine had existed in the treeline forest in the study area during the previous centuries we would probably have come across its remains as pine wood decays much more slowly than birch wood. Without the effect of dwarfshrub undergrowth on soil chemical processes podzolization would not have occurred in this place (cf. Broll, 2000). After the cooling climate had caused birch forest decline (see also Aas and Faarlund, 2001) the top soil of this Podzol eroded, probably because of wind action. Peat formation might have been initiated by the cooling or by a possible change of the hydrological conditions. Very likely the peat has to be considered a relic of a bog that filled this shallow valley after the Podzol had developed. The surface of the present peat layer

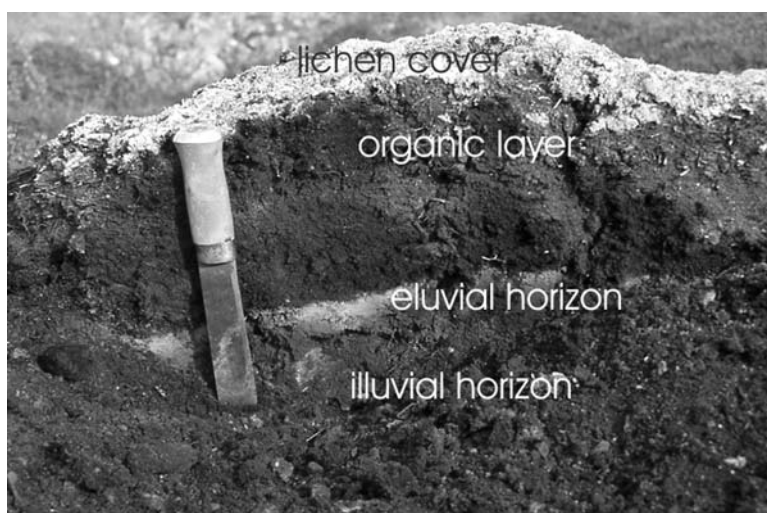


Figure 5 Peat accumulated on an eroded Podzol on a low step crossing a shallow valley on Staloskaidi at 303 m a.s.l. (cf. Figure 3d). The light grey eluvial horizon can be clearly seen. Photo by F.-K. Holtmeier, 17 August 2004

seems to roughly correspond to the previous bog surface (cf. Figure 3d).

Furthermore, our oldest dead wood samples (915 ± 55 yr BP, AD 1035–1175 and 960 ± 60 yrs BP, AD 1020–1165) date from this period (c.f. Figure 2). They probably reflect the general long-term retreat of the upper birch treeline that continued during the 'Little Ice Age', as might be concluded from the wood samples taken on Rodjanoaivi at about 362 m and 366 m a.s.l. that date back to AD 1320–1430 and AD 1440–1615. The gradual Holocene cooling culminated during the period (Grove, 1988; Grudd *et al.*, 2002; Kullman, 2005a). The generally low number of dead wood remains may be explained by rapid decomposition of birch wood. Wood remains can only persist for long periods within peat while those in the substrates of other places soon rotted away. Thus, subfossil birch wood seems to be under-represented.

The densely spaced, low peaty hummocks (10–30 cm, cf. Figure 3e) on the present gentle, treeless slopes, interfluves and other convex topography suggest the existence of former birch stands in these places. Although not every hummock contains birch relics, it may be safely assumed, however, that many dead stems and root stocks decayed rapidly without leaving visible or identifiable remains. The hummocks developed from organic matter accumulating around the stem base of the tree clumps, and these features can be observed below treeline at present. The comparatively short distances between the hummocks suggest open birch stands that looked quite similar to the present open birch stands at lower elevation. These observations support the hypothesis that the original upper mountain birch forest was open woodland (eg, Oksanen *et al.*, 1995; Kankaanpää, 1999). In any case, the former birch forest did not reach its climatic limit in a closed front.

Many of the dead wood samples collected in these sites are remains of birch stands that died towards the end of the 'Little Ice Age' or even later (cf. Table 1, Figure 2). Most likely these birch stands decayed first of all because of adverse climatic conditions. The cooling in northern Fennoscandia since the 1940s until about 1990 (eg, Koutaniemi, 1990) might have played an important role in this respect (see also Kullman, 1989a, for the Swedish Scandes). In our study areas, it is the combined effect of occasional (episodic) mass outbreaks of the autumnal moth (*Epiphyra autumnata*) and subsequent very cold summers, however, which prevented the recovery of birch, as has been observed also in contemporary outbreak areas (eg, Nuorteva, 1963; Holtmeier, 1974).

Owing to the decline of the birch stands at 380–400 m elevation the alpine zone extended downslope, and wind has increasingly eroded the exposed treeless topography (eg, Holtmeier *et al.*, 2004). The same process has been reported from the Swedish Scandes (Kullman and Kjällgren, 2000; Kullman, 2005a,c). There, the downwind advance of wind scarps amounts to 5–10 cm/yr, which appears to be much more rapid than the active wind scarps in our study area.

Although the Holocene cooling culminated some centuries prior to the twentieth century (Kullman, 2005a,b) in northern Europe, the living 100 to 200 yr old birches give evidence that even in this unfavourable period birch became established in relatively suitable places, such as wind-sheltered and snow-rich leeward slopes and shallow valleys not suffering from late-lying snow. The oldest living birch identified on Rodjanoaivi at 358 m a.s.l. was 225 years old (tree-ring age, Holtmeier *et al.*, 2003). Conversely, birch was not able to invade extremely wind-swept and heavily eroded topography, where wind erosion had steadily increased since the decay of the former birch forest (see also Kullman, 2005c). Grazing pressure was low at that time compared with the following period. For centuries

reindeer had been the main base of existence of the Sami people without having seriously threatened the existence of the birch stands in the treeline ecotone.

The relatively young age of many birch wood samples (cf. Table 1, Figure 2) support our hypotheses (Holtmeier *et al.*, 2004) that, at least in modern time, mass outbreaks of the autumnal moth combined with excessive reindeer grazing (Holtmeier, 1974, 2002, 2005b; Helle and Kajala, 1992; Kumpula and Nieminen, 1992; Helle and Kojola, 1993; Oksanen *et al.*, 1995; Väre *et al.*, 1996; Helle, 2001; Müller-Wille *et al.*, 2001) are responsible for decline of birch stands in the treeline ecotone. In northern Utsjoki, several mass outbreaks of the autumnal moth occurred during the last 150 years (1844, 1905–1909, 1927, 1957, 1965–1966; Kalliola, 1941; Nuorteva, 1963; Holtmeier, 1974, 2002, 2003; Holtmeier *et al.*, 2003; see also map in Kallio and Lehtonen, 1973).

The number of reindeer has always fluctuated in response to natural environmental factors (extreme winters, malnutrition, diseases, predators, etc.). However, the reindeer population has now increased because of herding practices to the extent that it has more than doubled since the mid 1970s. It reached its maximum in the end of the twentieth century (eg, Kumpula and Nieminen, 1992; Oksanen *et al.*, 1995; Burgess, 1999). In addition, summer grazing pressure considerably increased because of the lack of seasonal grazing practice (Helle, 1966; Holtmeier, 1974; Käyhkö and Pellikka, 1994). Intensification of reindeer grazing resulted in heavy disturbance of the ecological conditions (eg, Haapasaari, 1988). Also, use of birch as firewood over long periods by Sami people (cf. Müller-Wille *et al.*, 2001) may have contributed to the destruction of the birch stands in the treeline ecotone. The cutting of birch for fuel, however, has strongly decreased in the mountains in recent years (L. Müller-Wille, personal communication, 2005).

The birch rust (*Melampsorium betulinum*, cf. Lappalainen *et al.*, 1995; Helander *et al.*, 1998), not much considered so far as a treeline-relevant factor, may also have been involved in birch treeline decline because it increases birch mortality. On the other hand, birch rust infection probably impairs autumnal moth performance (Lappalainen *et al.*, 1995).

Reindeer grazing exceeding the natural carrying capacity hampered the recovery of the birch stands in the treeline ecotone affected by mass outbreaks of the autumnal moth (see also Lehtonen and Heikkinen, 1995; Oksanen *et al.*, 1995; Holtmeier, 2002, 2003; Holtmeier *et al.*, 2004; Holtmeier and Broll, 2005; Lempa *et al.*, 2005; Neuvonen *et al.*, 2005). Moreover, reindeer particularly impeded establishment of birch seedlings and also prevented the development of a closed plant cover on eroded sites, thus enhancing wind erosion (see also Kullman, 2005c). These effects might override possible positive influences of a warming climate. Thus, the situation is somewhat different from the southern Scandes, for example, where treelines (birch, pine and spruce) have risen during the twentieth century, a situation unmatched for the past 4000–7000 years (Kullman, 2003, 2004, 2005a).

Conclusions

The results presented here are in accord with the long-term treeline decline in northern Fennoscandia, which is well-documented in literature (see references cited).

The peat remains provide evidence of formerly more extensive peat layers that accumulated during the last 2000 years under cool and humid conditions. It was the cooling climate that primarily caused the decline of the original upper

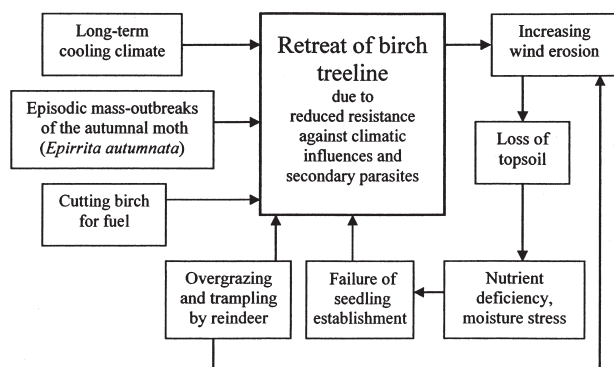


Figure 6 The causes and consequences of birch treeline decline

mountain birch forest. On closer inspection, however, the ecological interactions are likely to have been more complex in our study area (Figure 6). Episodic mass-outbreaks of the autumnal moth combined with cool summers have prevented the recovery of the birch stands and this has accelerated the decline of birch in the treeline ecotone. This has resulted in the downslope advance of the alpine zone after the Atlantic period. As a result wind erosion has increased considerably, destroying the shallow peat layers and removing the topsoil from wind-exposed topography. Wind erosion has been further enhanced in modern times because of overgrazing by reindeer.

These after-effects of the Holocene climatically triggered treeline retreat, combined with episodic mass-outbreaks of the autumnal moth and, more recently, overgrazing by reindeer are the factors preventing the birch forest from re-colonizing its former habitat during the present more favourable general climatic conditions.

Altogether, the radiocarbon-dated peat and dead wood samples, when seen in relation to the topographically controlled site conditions (cf. Holtmeier *et al.*, 2003, 2004) and the distribution pattern of the present birch stands, may contribute to a better understanding of landscape and treeline history in the study area. This is an essential basis for future treeline research, because the present ecological conditions in the treeline ecotone and treeline sensitivity to environmental change depend more on treeline and landscape history than might be usually expected (cf., Holtmeier and Broll, 2005).

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