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Early Holocene Appearance of Mountain Birch (*Betula pubescens* ssp. *tortuosa*) at Unprecedented High Elevations in the Swedish Scandes: Megafossil Evidence Exposed by Recent Snow and Ice Recession

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Abstract

Megafossil wood remnants (trunks and roots) of mountain birch (*Betula pubescens* ssp. *tortuosa*) were retrieved from the alpine tundra of the southern Swedish Scandes (the Sylarna Mountains). The samples have recently become exposed by rapid recession of glaciers and snow patches at three sites located 630 to 350 m higher than the present-day birch tree-limit and 350 to 80 m higher than the early Holocene pine limit. Radiocarbon dating yielded ages ranging between 8700 and 6200 B.P. (9700–7000 cal B.P.). This is the first direct evidence of past tree growth at such high elevations in the Scandes, relative to the modern tree-limit. The overall situation with uniquely high tree-limits and absence of glaciers suggests a climate with generally drier and warmer summers than during any later part (secular-millennial scale) of the Holocene. Corrected for glacioisostatic land-uplift, summers around 8700 B.P. may have been about 3°C warmer than at present. This inference is compatible with the Milankovitch model of orbital climate forcing during the course of the Holocene, implying a gradually increasing maritime climate (less seasonal), with a heavier snowpack. As a consequence, alpine snowfields started to develop over the period 8700–6200 B.P., causing demise and burial of the highest metapopulations of mountain birch. At lower elevations, where snow accumulation had previously been suboptimal for birch, this species could now benefit from a deeper and more persistent snow cover. Since about 7000 B.P., a distinct mountain birch belt has been a characteristic feature in this part of the Scandes. The exposure of mountain birch megafossils relates to substantial 20th-century warming, reaching a peak in the past few years. Evidently, this is an exceptional occurrence in the context of several past millennia.

Introduction

The species composition, structure and location of upper tree-limit ecosystems are under climatic control at broad spatial and temporal scales (Tranquillini, 1979; Kullman, 1998, 2001a; Holtmeier, 2000; Grace et al., 2002; Kjällgren and Kullman, 2002). Thus, reconstructions of their past limits may add to our understanding of paleoclimates as well as vegetational responses to past and future climate shifts.

Holocene tree-limit positions are most accurately defined from megafossil (trunks, roots, etc.) and macrofossil (leaves, needles, cones, etc.) evidence (Aas and Faarlund, 1999; Carcaillet and Brun, 2000; Kullman, 2001b; Payette et al., 2002). In the Swedish Scandes, extensive work on subfossil tree remains, preserved in peat and sediments above modern tree-limits, have shown the previous limits of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) (Lundqvist, 1969; Kullman, 1995, 1999, 2001a, 2001b; Kullman and Kjällgren, 2000). Analogous approaches in Finland and Norway have contributed to develop this specific approach to vegetation and paleoclimate history (Eronen and Huttunen, 1987; Selsing, 1996; Aas and Faarlund, 1999). Also in adjacent parts of Russia, important progress in this field has been made in recent years (Kremenetski et al., 1998; MacDonald et al., 2000). Megafossil surveys are still in their infancy and most published data on maximum tree-limit extensions during the Holocene are likely to be conservative minimum estimates.

The general tree species zonation on high mountains in northwestern Europe is characterized by a fairly broad vertical belt of predominantly mountain birch (*Betula pubescens* ssp. *tortuosa*) between the coniferous boreal forest (pine and spruce) and the treeless alpine tundra (Kullman, 1981a; Aas and Faarlund, 1996). The Holocene history of this Nordic mountain birch belt, that has replaced the pine-dominated Caledonian Forest, is still poorly known. A crucial and much debated question is whether such a vertical belt in its present-day discrete form existed permanently throughout the entire Holocene (cf. Aas and Faarlund, 2001). In particular, its elevational and regional differentiation during the early Holocene cannot be inferred from existing data.

Drawing entirely on megafossil evidence, Kullman (1995) inferred the existence of a distinct birch belt in the study region from shortly prior to 7000 B.P., when birch was found to have grown at least 100 m higher than the upper limit of pine. For earlier parts of the Holocene only a few birch megafossil recoveries have so far been reported from the Scandes (Barth et al., 1980; Kullman, 1995; Aas and Faarlund, 2001), with little prospect of defining their community context or full extension of the elevational distribution.

Recently, a focused megafossil study at a specific site in the southern Swedish Scandes (Kullman, 2002a) revealed that mountain birch (along with pine and spruce) had already colonized an early-emerging nunatak in the Late-Glacial (ca. 14,000 B.P.), about 400 m above the present-day birch tree-limit. Birch trees persisted at this high-elevation site (1360 m a.s.l.) more or less continuously until at least 5300 B.P.. During the same interval the tree-limit of pine dropped by about 300 m in response to gradual climate cooling, including the effects

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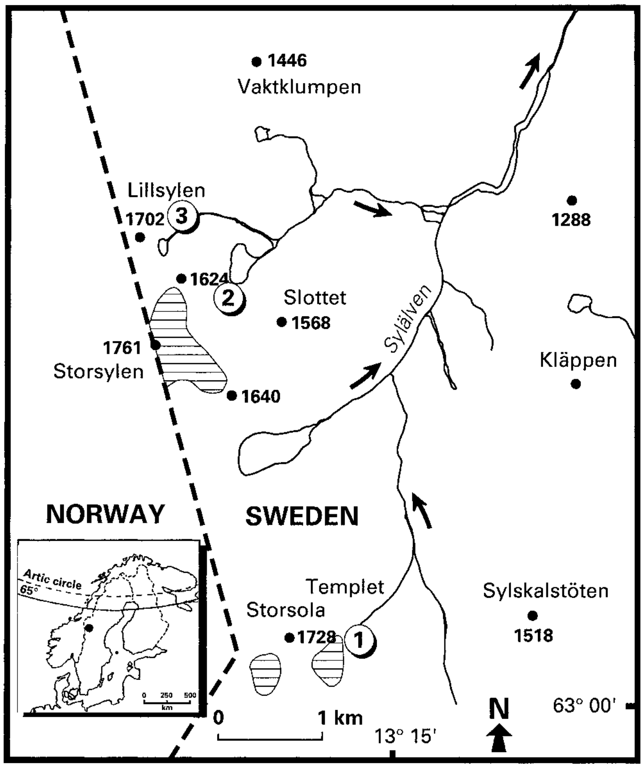

FIGURE 1. Location map showing the Sylarna Mts. and sampling sites 1 to 3. The altitudes of the highest peaks are given in m a.s.l. Existing glaciers are hatched.

of land-uplift from isostatic rebound (Kullman and Kjällgren, 2000). The coeval lack of apparent birch tree-limit decline on this specific locality, i.e. 1360 m a.s.l., suggests the hypothesis that the climatic birch tree-limit was substantially higher than this position during the earliest phase of the Holocene. This would imply that a more or less continuous birch belt could have existed, at least locally, above the upper limits of the conifers, just like the present-day zonation pattern. This issue could not be definitely tested at that study site, since this mountain is too low, reaching only 1420 m a.s.l.

This paper reports results from field-tests of the hypothesis that birch grew in a broad altitudinal belt above the boreal coniferous forest during the early Holocene, with the tree-limit located at least 500 m higher than its modern position. This figure is approximately the same as the total Holocene elevational decline of pine and spruce (Kullman and Kjällgren, 2000; Kullman, 2001b).

The feasibility of such a test has been doubted due to the sparsity of sufficiently deep peat accumulations at correspondingly high elevations, i.e. the only "archive" considered to exist for the present purpose. However, a new avenue of high-altitude megafossil pursuit has emerged during the last few years, as accelerated melting of glaciers and large snowfields has exposed detrital plant remains, which in certain cases have been preserved for many millennia by snow and glacial ice (Kullman, 2001c; Markels, 2002). This source of "fossil" data has previously been little observed or exploited in Scandinavia (but see Elven, 1978; Rapp, 1992), but is widely used in other parts of the world, particularly where glaciers extend downslope to near the upper forest margin (e.g., Luckman et al., 1993; Nicolussi and Patzelt, 2000; Hormes et al., 2001). By mean of this approach, surveys of past tree-limits may be extended to much higher elevations.

The Sylarna Mountains were selected as a suitable test area as they offer a multitude of different physiographic settings at sufficiently high elevations, in combination with the presence of small and currently wasting glaciers and perennial snowfields.

FIGURE 2. The Sylarna Mts. and the glacier Storsylglaciären viewed from the northeast. In the first decade of the 20th century, the lowest glacier tongue extended to about 25 m above the proglacial lake (1275 m a.s.l.) viewed in the foreground (Enquist, 1910). Site 2 is right at the inlet of the main meltwater stream to this lake. Photo: L. Kullman, 22 August 2001.

Study Area

LOCATION AND PHYSIOGRAPHIC SETTING

The Sylarna Mountains (63°01′N; 12°13′E) are located in the southern Scandes (Caledonides) of Sweden, right at the border between Sweden and Norway. The highest peak, 1761 m a.s.l., is in Norway, but terrain above 1700 m a.s.l. is also found in Sweden (Fig. 1). The area drains towards the northeast by the Sylälven river.

The entire massif rests on a high-plain at about 1000 m a.s.l. It is characterized by complex alpine relief, with sharp peaks, narrow crests, steep-sided rock slopes and deep cirque valleys with glacier niches (both empty and filled) (Fig. 2). The bedrock is made up of dark and very hard amphibolite, locally intersected with softer schists. Up to around 1200 m a.s.l., the solid rocks are covered by glacial till. At higher elevations, extensive boulder fields dominate the mountain landscape. Rockfalls, gelifluction, and wind erosion are active processes that constantly reshape the local topography.

The deglaciation of the highest peaks in the concerned region was well underway already by 14,000 B.P., whereas thinning residual ice filled the deeper valleys for some further millennia (Kullman and Kjällgren, 2000; Kullman 2002a). Currently, the Sylarna Mountains harbor three small glaciers, situated in east-facing cirques, where the prevailing snow drift from the west accumulates large snow masses. Two of these features may in fact be transitional between true glaciers and large snow/ice patches. The lowest frontal positions are between 1450 and 1600 m a.s.l. Their Holocene history have been studied only tentatively, but has been suggested to be of Neoglacial origin, initiated about 2500 yr ago (Lundqvist, 1969) or perhaps 1000 yr earlier, when substantial cooling and tree-limit recession took place in the region in response to delayed snow melt (Kullman, 2003a). These mountain glaciers are very close to the southern limit of modern montane glaciation in the Swedish Scandes, which may make them susceptible to subtle climate change.

PLANT COVER

A sparse tree cover, exclusively of mountain birch, is found close to the river Sylälven, 6 to 7 km east of the sampling sites. Small birch copses occupy sheltered south-facing slopes of the numerous morainic hillocks up to the tree-limit at 920 m a.s.l. (Fig. 3). During the past century, the local tree-limit advanced by some tens of meters altitudinally (Kullman, 1979). This is much less than the average for the region as a whole, which relates to the flat and wind-exposed (snow-poor) topography at higher elevations. The nearest outposts of mature *Pinus sylvestris* are found about 20 km northeast (680 m a.s.l.).

Above the tree-limit, the dominant plant cover consists of dwarf-shrub heaths (*Betula nana*, *Empetrum hermaphroditum*, *Vaccinium myrtillus*), snowbed communities, and mires. With increasing elevation, the plant cover becomes sparser and increasingly polarized between depressions with long-lasting snow cover and more or less snow-free crests. The snowbed communities are dominated by plants such as *Salix herbacea*, *Sibbaldia procumbens*, *Alchemilla alpina*, *Oxyria digyna*, *Viola biflora*, *Bistorta alpina*, and *Ranunculus acris*. The windblown crests display sparsely strewn specimens of *Juncus trifidus, Festuca vivipara, Saxifraga cespitosa*, *Huperzia selago*, *Cardamine bellidifolia*, and *Salix herbacea*.

A notable feature when discussing past distributional limits is that the Sylarna massif, above 1300–1400 m a.s.l., is characterized by several steep, south-facing rock and scree slopes with associated local climates favorable for plant growth. Therefore, many plant species reach their highest stations in the entire Swedish Scandes region (Kilander, 1955).

MODERN CLIMATE AND CLIMATE CHANGE

The climate is weakly maritime. The nearest meteorological station with long-term data is Storlien/Visjövalen (642 m a.s.l. and 32 km north). The mean temperatures (1961–1990) for January, July, and the year are –7.6, 10.7, and 1.1°C, respectively. The mean annual precipitation amounts to ca. 900 mm (all data from the Swedish Meteorological and Hydrological Institute). An automatic weather station has been operated since 1985 at 1030 m a.s.l. and 3 km northeast of the study site. The mean temperature for July is 7.9°C, while the annual precipitation is estimated to be 1000–1200 mm (Raab and Vedin, 1995).

Standard meteorological records at the Storlien/Visjövalen station reveal summer (June-August) warming by a linear trend ($p < 0.01$) of 1.1°C over the period 1901–2003. The scatter is large, however, and some significantly cooler decades occurred after the mid-century, with some tendencies for minor tree-limit descent (Kullman, 1997). The warmest and second warmest summers on record were 2002 and 1997, respectively. The winter temperature (December-February) has fluctuated with a larger amplitude on annual to decadal scales and the overall warming trend is less pronounced. Two distinct winter optima can be discerned during the 1930s and 1988–2002. The latter was 1.5 and 0.7°C warmer than the periods 1902–2002 and 1931–1940, respectively. The coldest winter on record was 1965/66, followed by 1969/70. Recent winter warming is a manifestation of a particularly intensive phase of the North Atlantic Oscillation (NAO) (cf. Hurrell and van Loon, 1997). Local precipitation trends are less reliable, although a tendency for annual precipitation to increase has characterized most of the past century, particularly since the 1970s.

ONGOING CHANGES OF ICE, SNOW AND PLANT COVER

Concomitant with the warming climate trend, the mountainscape has changed profoundly over the past century. Advancing natural tree-limits by a maximum of 140 m have, in certain topoclimatic settings, reduced the areal extent of the alpine tundra (Kullman, 1979, 2000, 2001a, 2001c). Recession of glaciers and perennial snowfields has exposed new ground for plant colonization. Geomorphological processes, e.g., many minor and major rock falls, rock slides, debris flows, and landslides at high elevations may relate to recent warming and the reduction of permafrost (cf. Rapp, 1992; Nyberg and Rapp, 1998).

Present-day comparisons with historical terrain photographs from 1908 (Enquist, 1910) and up to the present day reveal areal reduction of the existing glaciers by about 50% (Lundqvist, 1969; Kullman 2003a) (Figs. 2, 4). The recession accelerated during the long and hot summer of 2002, despite above-average winter precipitation that year (Kullman, 2003a). At the very end of the ablation period in early September in 2001, 2002, and 2003, large forefield areas downslope of glaciers and large quasi-permanent snowfields were melted out to a degree that was probably unique for hundreds or thousands of years. The newly exposed ground was entirely devoid of living lichens, bryophytes, and vascular plants. This was the setting of the recovered megafossil birch tree remains, which constitute the core of this paper. More or less complete late-summer thawing of snowfields, i.e. increasing length of the snow-free period, is a characteristic feature in the southern Swedish Scandes since 1996 or even earlier (Kullman, 2001c, unpublished data). As a biological consequence, the altitudinal limits of certain vascular plants have rapidly shifted upwards and species richness has increased in terrain that is not too wind-exposed (Kullman, 2002a, 2003b). For example, young seedlings and saplings of pine, spruce and birch have recently started to invade certain habitats in the alpine tundra up to 1500 m a.s.l. in the Sylarna Mts., where they were never recorded by previous intensive surveys (Kilander, 1955; Kullman, 1979, 1981b). Decreasing meltwater flow from snow patches during the late summer has triggered substantial expansion of grass and bryophyte vegetation at the expense of snowbed plants and bare mineral soil, respectively.

FIGURE 3. The nearest present-day tree-limit of mountain birch, east of the river Sylälven, 920 m a.s.l. Growth to tree-size of these stems was initiated during the warming peak in the late-1930s. Photo: L. Kullman, 5 August 1977.

LAND USE

The alpine landscape is extensively grazed by semidomestic reindeer, which have replaced the wild reindeer since the late-19th century. Reindeer numbers have increased throughout the past century. Grazing and trampling has reduced the cover of lichens in the bottom layer of some types of dwarf-shrub heaths and also enhanced the natural erosion processes at wind-exposed sites (Kullman, 1997). On the whole, reindeer exert both positive and negative impacts on tree regeneration and there is no obvious relation between fluctuating reindeer populations and tree-limit evolution during the past century (Kullman, 1979).

Methods

SAMPLING AND SPECIES IDENTIFICATION

During the late summers of 2001 and 2002, extensive areas in the forefields of glaciers and large snowfields were intensively searched for

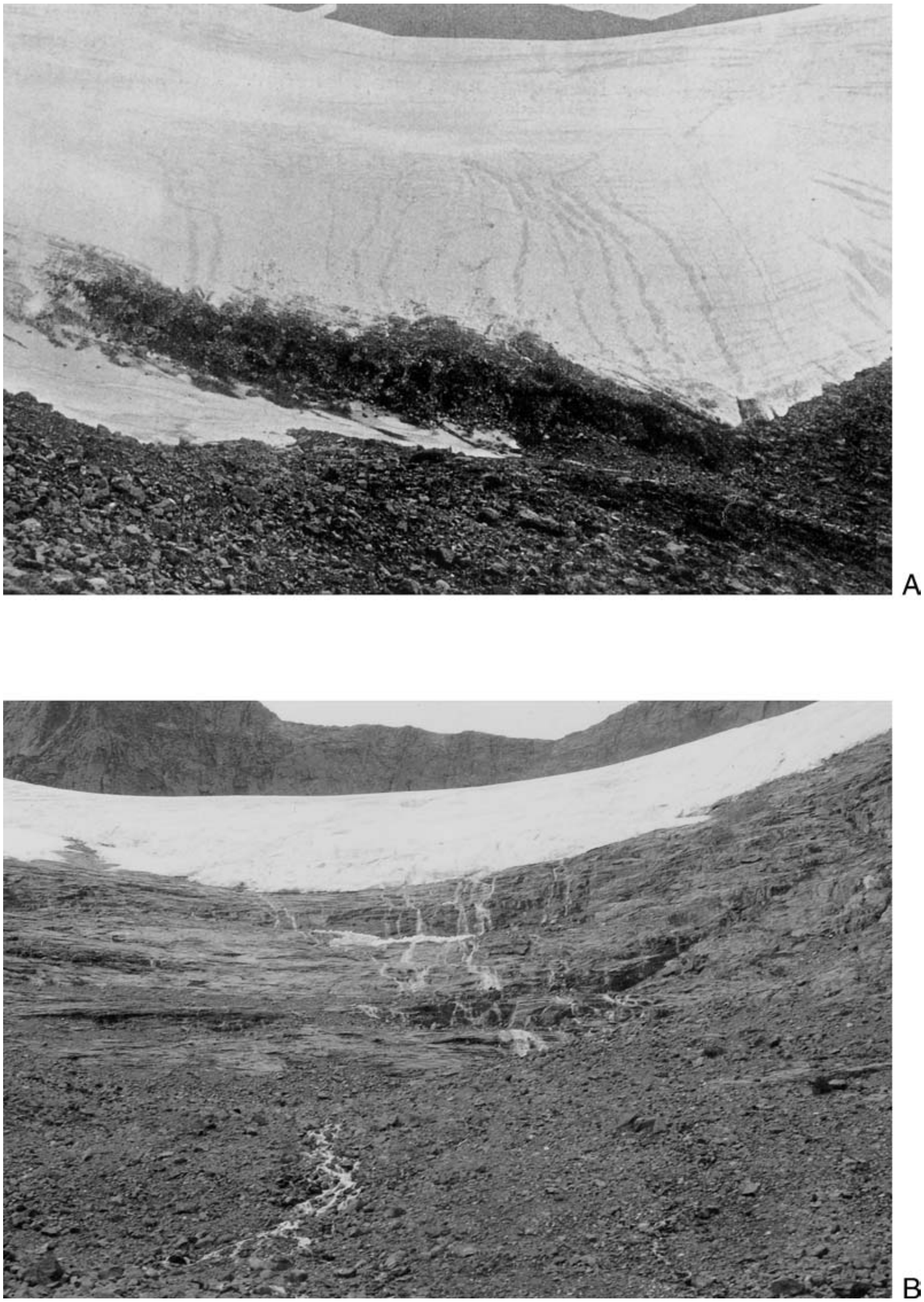

FIGURE 4. A: The lower edge of the glacier Storsylglaciären, 1300 m a.s.l. as it appeared on a photograph (late August 1908) by Enquist (1910). B: Substantial frontal recession has taken place over the past century. Photo: L. Kullman, 22 August 2001.

subfossil wood remains of any tree species. The elevations of primary concern were between 1200 and 1500 m a.s.l. The lower figure represents the highest published record of subfossil pine in the Sylarna Mountains (Kullman and Kjällgren, 2000). A major part of the surveyed area has been free of glacier ice and late-summer snow since the end of the Little Ice Age in the late 19th century. In addition, large nonglaciated areas (heaths, mires, lakes) at the same elevations have been screened for presence of megafossils. No attempts were made to uncover wood remnants possibly buried in frontal moraines.

Megafossil sampling was carried out at three distinct sites, numbered 1–3 in Figure 1 and described below:

- Site 1. Downvalley of the small glacier on the southeast-facing slope of Mt. Templet and in association with its main meltwater stream, 1340–1330 m a.s.l. All samples occurred at the margin of large snowfields and some of them were submerged in a small meltwater pool.
- Site 2. Downvalley of the glacier Storsylglaciären, where its main drainage forms a small delta of a proglacial lake

FIGURE 5. *The uppermost sampling site (no. 3) was at 1500 m a.s.l. Subfossil birch remains were recovered here within the nearest 30 m from the snow fringe. Complete absence of lichens and mosses suggest that late summer thawing of this zone is highly exceptional. Photo: L. Kullman, 21 July 2002.*

(Syltjärn), 1275 m a.s.l. Megafossil wood was deposited here, probably from nearby steep east- and southeast-facing slopes and is more or less covered by a thin moss layer of fairly recent origin.

- Site 3. Southeast-facing slope of Mt. Lillsylen, 1500–1490 m a.s.l. Detrital wood emerged among the blocks on a protalus rampart, adjacent to the lower fringe of a large snowfield extending at least 100 m higher upslope (Fig. 5).

No megafossils emerged outside these three sites. All wood samples that were found in the study area were retrieved, measured and submitted for radiocarbon dating. They were all positively identified as *Betula pubescens* coll. by the presence of bark fragments and distinguished from *Betula pendula* by a chemotaxonomical method (Lundgren et al., 1995).

DATING

Radiocarbon dating of the wood samples was performed by Beta Analytic Inc., Miami, Florida. The dates are reported and discussed in terms of conventional radiocarbon years B.P. (=AD 1950), in order to facilitate comparison with previous megafossil dates reported from this specific geographical region. In addition, calendar dates (cal B.P. ± 1 S.D.), calibrated according to Stuiver et al. (1998), are given in Table 1 and occasionally in the text.

Results

A total of ten samples of subfossil birch wood were found and radiocarbon-dated from three sites located between 1275 and 1500 m a.s.l. Wood of no other tree species was identified within this specific elevational belt. Notably, megafossils were not found outside the forefields of glaciers and large snow patches. The radiocarbon ages range between 8700 and 6200 B.P. (9700–7000 cal B.P.), with a tendency for the highest and lowest sites to harbor the oldest and youngest wood, respectively (Table 1).

TABLE 1

Radiocarbon dates of Betula pubescens *ssp.* tortuosa *with sample characteristics*

Site	Laboratory no.	^{14}C age ± 1 S.D.	Calibrated age ± 1 S.D.	Sample size (cm) (length × diameter)
1	Beta-172306	7630 ± 70	8440–8380	38 × 9
1	Beta-172307	7970 ± 50	9000–8710	40 × 7
1	Beta-172308	7570 ± 50	8400–8350	39 × 7
2	Beta-160105	6220 ± 80	7250–7000	55 × 11
2	Beta-172309	7180 ± 60	8020–7950	22 × 6
3	Beta-172310	8150 ± 60	9140–9020	18 × 7
3	Beta-172311	8710 ± 60	9740–9560	8 × 5
3	Beta-172312	8430 ± 70	9510–9420	12 × 6
3	Beta-122313	8030 ± 60	9020–8790	10 × 5
3	Beta-172315	7840 ± 70	8660–8550	14 × 7

Only short sections of trunks could be recovered, although their sizes and forms demonstrate the former presence of small erect trees (Table 1), comparable to those constituting the upper part of the modern subalpine birch forest belt (Fig. 2). The wood samples were in a state of preservation that allowed only short tree ring sequences to be seen. In some cases, however, distinct asymmetric ring patterns emerged on trunk cross sections, suggesting growth in a fairly steep topography with a deep and heavy snow cover.

Most of the recovered wood pieces were visibly exposed on the ground surface, i.e. without a stratigraphical context, among angular blocks of various sizes and trickling meltwater (Figs. 6, 7). A few were more or less concealed beneath newly established and living moss carpets in minor deltas of proglacial lakes (Fig. 8). All sites of wood deposition were obviously of secondary nature, and the wood can be characterized as detrital, i.e. it has been transported there from higher original growing locations, by slides, avalanches, or subglacial/subnival fluvial action. Thus, only minimum estimates of

FIGURE 6. *Detrital birch trunk emerging close to the snow margin, and dated 7970 ± 50 B.P. (Site 1). Photo: L. Kullman, 18 July 2002.*

FIGURE 7. The birch trunk displayed in Figure 6 was discovered at the left hand margin of the lower snow patch. Photo: L. Kullman, 18 July 2002.

total elevational shifts of the tree-limit during the Holocene could be made.

Some specimens showed small pebbles pressed into the wood, suggesting that they had spent most of their *post mortem* time under a heavy weight of an ice/snow and till cover. Other pieces of wood were in a fragmentary state of preservation, obviously reworked by meltwater action. One stem showed signs of having been sheared at the base. Practically all the recoveries were within a zone (100–200 m wide), currently entirely devoid of lichen-covered blocks, bryophytes, and vascular plants. Most of this ground has become exposed in the past few years.

Discussion

HOLOCENE LANDSCAPE HISTORY

The present results provide direct evidence for birch tree growth at unprecedented high altitudes during the early Holocene, and only the highest peaks in the region remained treeless at that time. The uppermost record, at 1500 m a.s.l. (8710 ± 60 B.P.), is 580 m above the nearest present-day birch tree-limit. This is likely to be a minimum figure, however, since the site of recovery was undoubtedly secondary, being a protalus rampart with a considerable downslope transport of blocks, soil and plant debris from adjacent cirque walls. Therefore, it seems reasonable to seek the original growing sites at least 1550 m a.s.l., i.e. beneath present-day permanent snow cover. Thus, tree birch may have grown as much as 630 m above its current tree-limit location.

Comparison with the megafossil tree-limit history of pine in the same region (Kjällgren and Kullman, 2000) reveals that birch trees may have attained positions 350 m higher than the upper limit of pine during the early Holocene. Today, the elevational separation of these specific tree-limits rarely exceeds 200 m in this region of the Scandes. These new results suggest an early Holocene landscape quite different from the present-day treeless and floristically depauperate alpine tundra. It will be an exciting task for future researchers to explore this topic in greater detail, using mega- and macrofossil records.

The present findings support, to some extent, the initial hypothesis that shortly after the regional deglaciation, birch grew above the pine-dominated Caledonian Forest, that initially clothed the valleys. However, the structure and regional coherence of such a belt at this early period cannot be inferred from existing data. Notably, these derive from a very special kind of environment, primarily selected as suitable for long-term preservation of wood remains. It is an open question whether this site was more favorable than surrounding mountain landscapes also for the *growth* of birch. In fact, the study area seems to possess such qualities. This is explicitly manifested by rapid recent invasion of tree saplings (birch, pine, spruce, and rowan) up to the same elevations as the recovered megafossils in response to warming during the past few decades (Kullman, 2002b, 2003b). It may well be that early postglacial tree growth of mountain birch was consistently restricted to such scattered high-altitude, outlying sites, with favorable topographical and local climatic conditions. In particular, an ample snow cover (cf. Kullman, 2002a) could locally have provided optimal conditions for establishment of metapopulations of mountain birch in a mountainscape otherwise characterized by too little snow for the comfort of this species, generally associated with fairly deep snowpacks and long winters (Kullman, 1981a; Aas and Faarlund, 1996). Moreover, existing megafossil (Kullman, 1995) and pollen data (Segerström and von Stedingk, 2003) from the lower reaches of the same major catchment area as the study site indicate that the mountain birch ecosystem attained its major areal development after approximately 7000 B.P.. Certainly, a general and broad birch belt reaching as high as 1500–1600 m a.s.l. prior to that would have left a fundamentally different fossil record. Likewise, in northernmost Sweden, megafossil data do not support the existence of a vertical (monospecific) birch belt during the time span under discussion here, but rather a tree-limit ecotone composed of mixed pine and birch stands (Kullman, 1999). Farther north (Norway), pollen and some macrofossil data have been interpreted as a pure birch forest belt during the early Holocene (Vorren et al., 1996; Jensen et al., 2002). Notably, however, very little megafossil research has been executed in this region.

Conceivably, the megafossils uncovered in pronounced snow accumulation settings may represent gradual population demise and burial in response to increasing snow cover over the period 8700–6200 B.P.. Concurrently, birch existed, although fairly scarcely at lower elevations, where it gained in landscape-scale dominance following the later part of the above-mentioned time interval (Kullman, 1995). Different lines of evidence from the southern Norwegian Scandes suggest that repeated phases of strong snow-avalanche activity commenced during the period concerned (Blikra and Selvik, 1998; Seierstad et al., 2002).

In conclusion, it is possible that the development of a deeper and more persistent snow cover (8700–6200 B.P.) exterminated the early-Holocene outlying birch populations, but favored growth, densification and coalescence of birch populations at lower elevations. From now on, a coherent birch belt of modern mode may have started to develop above the receding pine tree-limit, as outlined by megafossil data of both birch and pine (Kullman, 1995).

It is an exciting possibility that the early Holocene "birch pockets" at high elevations may rapidly come into existence again in response to predicted future global warming (SWECLIM, 2001), an assumption based on recent observations of tree sapling invasion into high-alpine tundra (Kullman, 2002b, 2003b). Thus, tree-limit adjustments will not necessarily manifest as displacements of distinct bands of woodland (cf. Bush, 2002).

PALEOCLIMATIC INFERENCES

By analogy with modern tree-limit patterns and responses (Malyshev, 1993; Aas and Faarlund, 1996; Kullman, 2001a; Kjällgren and Kullman, 2002), the all-time-high birch tree-limit during the early Holocene indicates warmer and drier conditions than present summers and possibly the warmest summers of the entire postglacial period. Widespread early Holocene tree growth in close spatial association with sites of present-day glaciers and large perennial firn patches suggests that at least the latter landscape element was virtually absent (i.e. higher glaciation limit) for a minimum period bracketed by 8700 and 6200 B.P., as inferred also for other glaciers in the South-Central Scandes (e.g., Nesje and Kvamme, 1991). In addition to warmer summers, this situation may also reflect lower winter precipitation and/or modest snow-accumulating winds. This general character of the early Holocene climate is compatible with paleoclimatic models based on the Milankovitch theory of orbital climate forcing (COHMAP, 1988; Berger, 1989), implying higher summer radiation and thus warmer summers than present. Virtually the same inferences can be made from the tree-limit history of *Pinus sylvestris* in the study region (Kullman and Kjällgren, 2000) and from combined pollen-macrofossil data in North Norway (Jensen et al., 2002). Under these circumstances, i.e. a stronger insolation regime, the existence of outlying stands in the topoclimatically complex mountainscape makes sense. These inferences concerning the early postglacial climate contrast with the idea of an oceanic climate in northern Scandinavia in the early Holocene (e.g., Seppä and Hammarlund, 2000)

In principle, the vertical difference between the highest postglacial birch record and the present-day tree-limit position, i.e. 630 m, may represent decrease of birch-relevant (summer) temperatures by 3.8°C, applying a crude elevational lapse rate of –0.6°C for 100 m altitudinal increase (Laaksonen, 1976). Tentative correction for glacioisostatic land-uplift (Dahl and Nesje, 1996) reduces this figure to ca. 3.0°C. This calculation suffers from some uncertainties, e.g., possible spatial and temporal variations of the lapse rate (cf. Mook and Vorren, 1996) and the vertical incoherence of the upper birch distribution during the early Holocene. Nonetheless, this lapse rate–based reconstruction gains in credibility by the finding that a maximum of 140 m birch tree-limit rise during the past century corresponds to 1°C summer warming (see above), i.e. near what would be predicted by the lapse rate used above. Moreover, the early Holocene figure obtained compares quite well with independent paleoclimatic reconstruction and models from the Scandes and adjacent regions (COHMAP, 1988; Kullman, 1999; Shemesh et al., 2001; MacDonald et al., 2002; Bigler et al., 2003), but exceeds other reconstructions (Nesje and Kvamme, 1991; Rosén et al., 2001; Bigler et al., 2002). These discrepancies may represent both regional differences and different methodological approaches. The obtained Holocene tree-limit/climate trend in Scandinavia agrees well with analogous reconstructions in various regions of North America and the European Alps (e.g., Ritchie et al., 1983; Luckman, 1990; Clague et al., 1992; Pellat and Matthewes, 1994; Munroe, 2003; Ali et al., 2003), which further supports a causal interpretation in terms of "orbital forcing."

FIGURE 8. Large piece of a birch trunk uncovered close to the inlet into the proglacial lake below the glacier Storsylglaciären (Site 2). This specimen has been raised from its original position beneath a fairly recent moss cover. Radiocarbon-dating yielded an age of 6220 ± 80 B.P.. Photo: L. Kullman, 22 August 2001.

RECENT GLACIAL AND NIVAL RECESSION IN PERSPECTIVE

Birch wood rapidly decomposes unless it is immediately covered by peat, compacted till, glacier ice or firn. The megafossil birch remnants discussed here were not covered by peat when found. They all occur within the limit of the maximum Little Ice Age glacier extension. It is reasonable to assume that they have been covered by ice/snow and till since their death and burial, i.e. 8700–6200 B.P., and up to the very recent past. Most certainly they would not have "survived" more than a few, possibly no, previous release periods of similar duration as the past century and subsequent reburial and compression by a heavy snow and ice pack. Thus, it is to be concluded that in this part of the Scandes, ice and snow recession during the warm 20th century has recently reached a magnitude that is likely to be exceptional in the perspective of several millennia. Analogous deductions in terms of summer temperature for the same region have been drawn by matching 20th century tree-limit rise of pine and mountain birch with their long-term (Holocene) histories (Kullman and Kjällgren, 2000; Kullman, 2003a). This anomalous recent reduction of snow and ice in the alpine landscape fits a general worldwide trend (Haeberli and Beniston, 1998; Luckman and Kavanagh, 2000; Bradley, 2000; Thompson, 2000; Thompson et al., 2002; Markels, 2002), signifying a fundamental break in the Neoglacial cooling trend (Luckman, 1998; Kullman, 2003a; Mann and Jones, 2003). The present discoveries indicate that the recent warming, if continued, can provide paleoecological science with unique opportunities to date and examine frozen plant remains that are becoming uncovered.

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