The Official Journal of the International Association for Landscape Ecology, Chapter Germany (IALE-D)
Landscape Online
International Peer-Review Free-Access Online

Received: 27.06.2011 Received in revision: 18.09.2011 Accepted: 12.10.2011 Published: 07.12.2011

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Landscape Online 26, 1-38 . **DOI:10.3097/LO.201126**

Recent Glacier Recession – a New Source of Postglacial Treeline and Climate History in the Swedish Scandes

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Abstract

Climate warming during the past century has imposed recession of glaciers and perennial snow/ice patches along the entire Swedish Scandes. On the newly exposed forefields, subfossil wood remnants are being outwashed from beneath ice and snow bodies. In Scandinavia, this kind of detrital wood is a previously unused source of postglacial vegetation and climate history. The present study reports radiocarbon dates of a set of 78 wood samples, retrieved from three main sites, high above modern treelines and stretching along the Swedish Scandes. In accord with previous studies, pine (*Pinus sylvestris*) colonized early emerging nunataks already during the Late Glacial. Around 9600-9500 cal. yr BP a first massive wave of tree establishment, birch and pine, took place in "empty" glacier cirques. Both species grew 400-600 m above their present-ay treeline position and the summer temperatures may have been 3.5 °C warmer than present. In respons to Neoglacial cooling, treelines of both birch and pine descended until their final disappearance from the record 4400 and 5900 cal. yr BP, respectively. During the entire interval 9600 to 4400 cal. yr BP, birch prospered in a 100-150 broad belt above the uppermost pines. The recent emergence of tree remnants in the current habitats relates to the contemporary episode of climate warming, possibly unprecedented for several past millennia. It is inferred, by an anology with the past, that in a future scenario with summers 3.5 ° warmer than present, the birch treeline may rise by 600 m or so.

Keywords:

climate change, glacier forefields, megafossil trees, vegetation history, paleoclimate, mountain birch, pine, Holocene

Introduction

World-wide, post-Little Ice Age climate warming has fundamentally altered the preconditions for physical and biological systems in alpine and subalpine/subarctic regions (Kullman 2002a, 2010a,b; Fagre et al. 2003; Moore 2003; Smol et al. 2005; Oldfield 2005; D´Arrigo et al. 2006; Barry 2006; Shiyatov et al. 2007; Kaufmann et al. 2009; Nesje 2009; Thompson et al. 2009; Nagy & Grabherr 2009; Akasofu 2010; Callaghan et al. 2010; Hallinger et al. 2010). Arctic and alpine ecological systems have responded perceivably to warmer climatic conditions by increasing species richness, changed abundances and upshifts of range-limits for plants and animals (Grabherr et al. 1994; Hughes 2000; Kullman 2004a, 2007a,b; Walther et al. 2005; Parmesan 2006; Erschbamer et al. 2009; Kullman & Öberg 2009; Leonelli et al. 2011; Feeley et al. 2011).

Provided that currently observed climatic and biotic trends continue or accelerate, there is an urgent need to project the consequences for future landscape evolution. In this context, it is our conviction that such an endeavour has to draw essentially on experiences of past ecological performances (cf. Davis 1989; Petit et al. 2008). Responses of the alpine treeline and the forest-alpine tundra ecotone are crucial in this respect, since presence/absence of a tree cover has a steering effect on the entire plant cover structure and biodiversity patterns. Treelines integrate climate beyond the annual scale and may serve as leading indicators of ecosystem-wide biotic changes (Hall & Fagre 2003; Kullman 2007a,b). Moreover, understanding of the dynamics of the forest-tundra interface is crucial for realistic regional and global climate modelling, since the location, extent and structure of this boundary may feed back on the entire climate system (Betts et al. 2000; Grace et al. 2002; Harding et al. 2002; Salonen et al. 2011).

Given a common upslope temperature lapse rate of -0.6 °C/100 m (Laaksonen 1976) and a mid-range scenario of warming by 3-3.5 °C over the next 100 years (ACIA 2004; Räisänen et al. 2004; IPCC 2007), the upper (alpine) border of closed forest would ideally advance by about 500-600 m in elevation (MacArthur 1972; Peters 1990). In that hypothetical case, and assuming an ubiquitously perfect climate-treeline relationship, only small and isolated fragments of alpine tundra would be left in the Scandes (Moen et al. 2004; Bernes 2007), supposedly with cascading effects on the biotic composition of the landscape (Hinzman et al. 2005). Based on regional treeline performance during the past century, the likelihood of such a treeline scenario as a general outcome may be questioned (Kullman & Öberg 2009; Kullman 2010a). For example, strong winds, poor snow cover, lack of fertile soils, dispersal obstacles and land use could prevent or reduce broad-scale elevational advance of continuous upper birch treelines into high-alpine landscapes even in a climate much warmer than present (Woodward 1993; Holtmeier & Broll 2005; Elliot & Kipfmueller 2010; Kullman 2010a).

For the Scandes, the main concern is for the subalpine birch belt, dominated by broadleaved deciduous mountain birch (*Betula pubescens* ssp. *czerepanovii*). Currently, this belt fringes the alpine tundra and has a vertical extent of 50-300 m. Downvalley, it merges with evergreen coniferous forest of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). As a rule, the treeline of spruce extends higher than that of pine. A detailed account of the structure of the treeline ecotone is given by Kullman (2010a).

As stated above, evaluation of the possibility for future tree growth by mountain birch or other tree species as much as 500-600 m above today´s treelines, is most confidently evaluated by the use of paleoecological analogues. For that purpose, megafossil/macrofossil analysis appears to be the sharpest tool (Kullman 1995; Kullman & Kjällgren 2000; Aas & Faarlund 1988, 2000; Barnett et al. 2001; Bergman et al. 2005; Eide et al. 2005; Paus 2010). This approach implies that subfossil tree remnants (logs, pieces of wood, roots, twigs, etc.) are systematically searched for at locations high above the current treeline, where they can provide information on the possible presence of trees, both in time and space. In the Scandes, the understanding of Holocene treeline history, mainly based on pine, has expanded to a higher level of certainty during the past few decades by this approach

(Karlén 1976; Eronen & Huttunen 1993; Moe 1994; Selsing 1998; Kullman 1995, 2002b; Aas & Faarlund 2000; Kullman & Kjällgren 2006; Paus 2010; Öberg & Kullman 2011). In addition, some recent pollen analytical studies have added detail to this issue (e.g. Segerström & von Stedingk 2003; Bergman et al. 2005; Hörnberg et al. 2006; Paus 2010). The emerging overall model is one of consistent treeline descent and a shift from pine to birch predominance throughout most of the Holocene, ultimately in response to decreased summer solar insolation and associated progressive cooling and decreased seasonality (Barnett et al. 2001; Shemesh et al. 2001; Hammarlund et al. 2004; Kullman & Kjällgren 2000, 2006; Paus 2010).

The Holocene elevational history of the subalpine birch forest belt has for long been intensively debated, but remains unclear in the absence of conclusive evidence. In particular its elevational extent and permanency throughout the Holocene have been matters of controversy (e.g. Smith 1920; Nordhagen 1933; Moe 1994; Aas & Faarlund 1988, 2000; Kvamme 1993; Gunnarsdóttir 1996; Torske 1996; Barnett et al. 2001; Kullman 2001a, 2004b, 2006; Eide et al. 2005). This enigma mainly relates to the lack of traditional preservation media for tree megafossils at high elevations, e.g. sufficiently deep peat and raw humus layers, suitable for long-term preservation of wood remnants (cf. Smith 1920). In addition, birch wood decays rapidly and the prospect of finding megafossils at the particularly high elevations, contemplated for the present study, has been considered virtually non-existent.

Based on existing megafossil and pollen data (cited above) and modern spatial response patterns to climate warming (Kullman & Öberg 2009; Kullman 2010a), we hypothesize that during the early Holocene, local birch groves and solitary trees existed at high-elevation sites, predominantly where topography favours wind-driven snow accumulation in a matrix of windswept alpine tundra (cf. Smith 1920; Kullman 1994, 2001a, 2004b; Barnett et al. 2001).

Figure 1: Iron arrowhead discovered at a high-alpine site in the southern Swedish Scandes (Mt. Getryggen, 1372 m a.s.l.), dominated by an extensive snow patch until the past few decades. Typologically, it dates about 900 to 1000 years back in time and was probably lost in connection with reindeer hunting, according to archaeologist Anders Hansson, Jamtli Museum, Östersund.

During the past few decades, a new avenue of hypothesis testing and deciphering alpine paleoecology and vegetation history has opened high above the upper limit of deep peat deposits. In many parts of the world, ongoing loss of glacier volume and area, in concert with recent (post-Little Ice Age) climate warming (e.g. Holmlund 1993; Baroni & Orombelli 1996; Oerlemans 2005; Dyurgerov & McCabe 2006; Thompson et al 2006; Menounos et al. 2009; Nesje 2009; Briner et al. 2010), has exposed a plethora of biological remains and archaeological artifacts (Fig. 1), representing virtually the entire Holocene epoch (e.g. Luckman 1998; Hormes et al. 2001; Krajick 2002; Farnell et al. 2004; Schlüchter & Jörin 2004; Humlum et al. 2005; Dixon et al. 2005; Nicolussi et al. 2005; Dove et al. 2005; Koch et al. 2007; Thompson et al. 2006; Grosjean et al. 2007; Wiles et al. 2008; Benedicht et al. 2008; Jörin et al. 2008; Thompson Davis et al. 2009; Buffen et al. 2009; Scapozza et al. 2010).

Recently, the feasibility of using this potentially rich source of paleovegetation information, was confirmed by minor exploratory studies at the fronts of some Swedish glaciers and semi-permanent snow/ice patches (Kullman 2002b, 2004a,b). Thus, it became clear that also in the Swedish Scandes, glacier forefields and rims of perennial snow patches, which have recently been freed from ice and snow, may expose various kinds of ancient biological remains, useful for paleovegetation reconstruction. In the Sylarna Mts., where the lower glacier margins have retreated by c. 150 m altitudinally over the past 100 years (Öberg & Kull-

ISSN 1865-1542

man unpubl.), detrital wood remnants of mountain birch were exposed on the ground surface or partly buried in frontal moraines. These locations were 350-600 m higher than the modern treeline of mountain birch and dated to between 8700 and 6200 cal. yr BP (Kullman 2004b).

Except for the last-mentioned studies, this source of robust and spatial-precise information concerning past tree growth, glacial history and paleoclimate is previously virtually unused in Scandinavian paleoecology and vegetation history, but see Liestøl (1962). This is even more remarkable, since a wealth of archaeological finds have been made in these environments, following the early phase of climate warming and associated glacier recession in the 1930s (e.g. Faegri 1933; Farbregd 1991). In addition, large quantities of subfossil remains of tree-sized birches were recorded in front of receding glaciers in Iceland already in the 1930s (Ahlmann 1938; Ives 1991).

Against the background outlined above, the main objective of this study is to constrain the maximum elevation, structural patterns and ecological correlates of high-elevation tree growth during the early Holocene, when summer temperatures in the Scandes may have been at least 3 °C warmer than today (Nesje et al. 1991; Moe 1994; Shemesh et al. 2001). Tentatively used, and concurrent with other paleodata and recent treeline performances, obtained results may serve as a paleoanalogue for the evolution of the forest-alpine tundra ecotone in a hypothetically warmer future. For this specific purpose, we analyze by radiocarbon-dating an extensive set of megafossil tree remains, retrieved from the forefields of rapidly receding glaciers and snow/ice patches along the entire Swedish Scandes.

Complementary to the entire Holocene history, an ecologically relevant and indicative scenario of future treeline performance presupposes accurate knowledge of recent treeline positions and dynamics by the same tree species (cf. Luckman 1990). For the two southernmost main study areas, this prerequisite was fulfilled (e.g. Kullman 1991; Bergman et al. 2005; Kullman & Öberg 2009). However, comparable data, based on the same strict treeline definition, was virtually lacking for the Abisko-area in northern Sweden, although some more general studies exist (Sonesson & Hoogesteger 1983; Holmgren & Tjus 1996). This motivated a complementary sampling effort in this area, particularly as there are suggestions of deviating climate sensitivities and drivers of treeline dynamics in northernmost Sweden during the past century (Dalen & Hofgaard 2005; Hofgaard et al. 2009; Van Bogaert et al. 2011). In addition, the postglacial treeline history of this area is suggested to differ significantly from other regions in the Scandes and adjacent parts of northern Finland (e.g. Berglund et al. 1996).

Methodological approach

The study comprises three main glacier areas, distributed along a total distance of ~700 km between the southernmost and northernmost part of the Swedish Scandes (Fig. 2). Except for large-scale geographical position, a criterion for selection of local sampling sites was the existence of glaciers extending down to the concerned elevations and with some published historical records.

In detail, the field sampling strategy implied that recently exposed forefields of alpine glaciers and perennial snow/ice patches were systematically searched for the presence of megafossil wood remnants useful for radiocarbon dating. In addition, great effort was devoted to scrutinize adjacent alpine tundra at the same and higher elevations for megafossils. The recovered specimens were taken to the laboratory and subsequently passed to radiocarbon dating, performed by Beta Analytic Inc., Miami (USA). In most cases, species identification has been unambiguous and based on bark fragments attached to the wood. A few particularly enigmatic samples were analyzed by Erik Danielsson/VEDLAB. Only complete wood pieces, i.e. no composite samples, were dated. With these premises, the risk for erroneous dating results of ancient wood is virtually negligible.

Throughout, radiocarbon ages are expressed as calibrated years before present (cal. yr BP), with “present” = 1950 AD. Calibration was conducted using CALIB 5.0.2 software (Stuiver et al. 2005) in combination with INTCAL04. In the text, the intercept values of radiocarbon age with the calibration curve are used for simplicity. In cases of multiple intercept ages, the midpoint between the oldest and youngest intercept was used. Dendrochronological dating was not found to be meaningful due to the small size and strong decay of most of the recovered subfossil tree remnants. Altitudes of sampling sites were obtained to the nearest 5 m with a GPS navigator (Garmin 60CS), repeatedly during the day calibrated against topographical maps. The nomenclature of vascular plants refers to Mossberg & Stenberg (2003).

"Treeline", a recurrent and central concept used in this study, is defined for each species as the maximum elevation for trees with a minimum height of 2 m (cf. Kullman 2010a). This strict and narrow definition is particularly motivated in the present case, as we strive to compare past and present treeline positions. We have reasons to believe that the treeline, rather than any more or less arbitrarily defined "forest line", provides the most clear-cut relation to the regional climate and its variations in space and time (cf. Kvamme 1993; Körner 2007; Kullman 2010a).

In many parts of the world, a general enigma for the evaluation of treeline dynamics is to separate effects of climate change and land use abandonment (cf. Hofgaard 1999; Karlsson et al. 2007). With the present definition of the treeline, however, there is no evidence from the study areas that neither its past nor its present positions relate to land use or any kind of disturbance history, e.g. forest fire, insect attacks or geomorphic instabilities (Kjällgren & Kullman 1998). In this respect, the Swedish Scandes differ from many other mountainous regions, e.g. in Norway, where the use of the treeline ecotone (livestock grazing and haymaking) has been more intense (cf. Bryn 2008; Rössler 2008). The relative naturalness of Swedish treelines and their dynamics is emphatically demonstrated by the contemporary phase of treeline advance, which frequently takes places in steep, virtually inaccessible slopes where humans and grazing animals have always been rare visitors. Moreover, establishment of closed forest stands in the treeline ecotone is currently largely confined to the fringes of contracting snow beds, where a primary link to recent climate evolution is obvious (Kullman & Öberg 2009). In this context it should be mentioned also that in the realively continental climate of the Swedish Scandes, the vertical distance between glaciers and land utilized for agricultural purposes is relatively large. Thus, human activities in the glacier forefields have always been limited or absent and therefore they are ideal arenas for the study of natural treeline change (cf. Nicolussi et al 2005).

Recent treeline dynamics at six localities in the Abisko-area was assessed by ground observations, combined with assessment of individual tree ages. Data on treeline elevations (m a.s.l.) at these sites in the early 1950s were provided in 1971 to Leif Kullman by Dr. Gustaf Sandberg, the former director of Abisko Scientific Research Station. In 1972, the tallest, "veteran-looking" birches around these elevations were bored 2 m above the ground level (treeline definition) in order to elucidate the year when this height was reached, thereby testing the accuracy of Sandberg´s records. In all cases, it turned out that tree-sized birches had grown at the alleged elevations at the stated point of time, but not higher upslope. In connection with this sampling effort, the actual treeline elevations were estimated, by use of a barometric altimeter, calibrated against topographical maps. The most recent treeline recordings (GPS data) were made in 2009 and 2010. These measurements confirmed (± 5 m) the altimetry made by the early 1970s, as some of the old treeline markers could be relocated.

Study areas

The three main study areas, from south to north along the Swedsih Scandes (Fig. 2), are named and numbered as follows: Helags/Sylarna (1-5), Tärna (6-7), Abisko (8-12). Each main area embraces different sampling sites (within brackets), numbered according to 1A, 1B, IC, etc. Location data and site characteristics are presented below. Geographical names are given in "Swedish", according to official topographic maps. In addition to the sites where megafossils were found, several similar localities, both at higher and lower elevations were investigated. As the results were negative, no details are given.

Figure 2: Location map showing the three main study areas along the Swedish Scandes.

3.1 *Helags/Sylarna*

In this area four niche glaciers and one ice patch have been focused: Helagsglaciären (1), Tempelglaciären (2), Storsylglaciären (3), Lillsylen (4) and Ekorrglaciären (5):

1. Helagsglaciären (62°54´N; 12°27´E) is the southernmost glacier in the Swedish Scandes. It is situated in an E-facing cirque of Mt. Helagsfjället, 1797 m a.s.l. The total size is estimated to 0.5 km^2. The bedrock consists of amphibolites and gneisses. The glacier was mapped in 1908 by Enquist (1910). Subsequently and predominantly during the 1930s, substantial recession has taken place, particularly in the central and western parts (Lundqvist 1969). Thereafter no detailed studies have been carried out, although it appears that further size reduction has occurred during the past decade or so. Today, the lower margin of the eastern part of the glacier is about 1430 m a.s.l. This is the section most relevant for the present study (Fig. 3). The closest treelines (2010) for mountain birch, pine and spruce have all advanced to higher positions during the present century and are currently located, 955, 850 and 915 m a.s.l., respectively (Fig. 4).

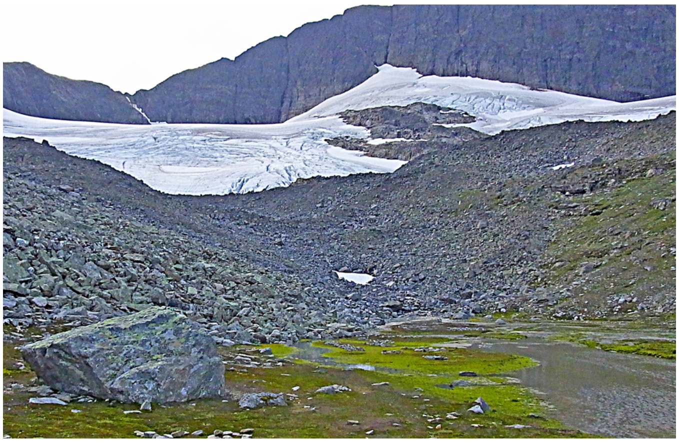

Figure 3: Helagsglaciären (1) viewed westwards from 1345 m a.s.l. 2006-10-15.

2. Tempelglaciären (63°00´N; 12°14´E) is located in an E-facing cirque belonging to Mt. Storsola, 1728 m a.s.l. (Fig. 5). Amphibolites with softer schists make up the bedrock. The lower extension is marked with a distinct frontal moraine, 1415 m a.s.l. Comparing the present-day situation with photographs taken in 1908 by Enquist (1910) visualizes that the front has withdrawn only marginally, although the glacier now appears substantially thinner. Large perennial snow and ice patches occur in the slopes at altitudes below the frontal moraine. The closest treelines (2010) for mountain birch, pine and spruce are located, 920, 770 and 815 m a.s.l., respectively.

Figure 4: The nearest treeline of birch (2010) is located 7 km east of Helagsglaciären. Since the early 20th century it has shifted upslope by 75 m. 2010-08-12.

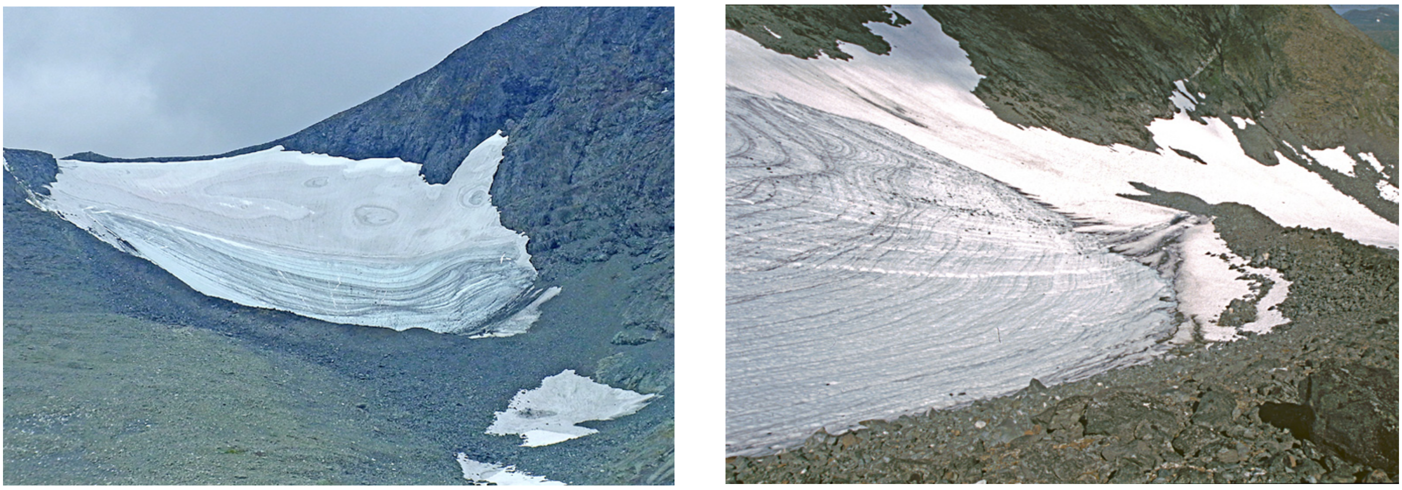

Figure 5: Left. Tempelglaciären (2) seen from the east. The lower terminus fringes an extensive frontal (Little Ice Age) moraine. 2009-09-10. Right. Close-up view of the tongue at the proximal side of the moraine, 1415 m a.s.l. 2005-08-15.

3. Storsylglaciären (63°01´N; 12°13´E) occupies a cirque facing NE on Mt. Storsylen, 1743 m a.s.l. The glacier covers an area of c. 0.25 km². Enquist (1910) recorded the lowest frontal position (1908) at 1300 m a.s.l., close to the small proglacial lake, Syltjärnen (Fig. 6). Until 2007, the total elevational withdrawal was 153 m. The recession was well underway by the 1930s (Mannerfelt 1945; Lundqvist 1969), as evidenced by matching now-and-then photographs. Perceptible ice loss has continued between 2001 and 2010 (Fig. 7). For geology and modern treelines, see Tempelglaciären (2).
4. Lillsylen (63°02´N, 12°13´E) is the site of a former small glacier (Enquist 1910), currently replaced with rapidly disintegrating perennial snow and ice patches (0.15 km²), in the E-facing slope of Mt. Lillsylen, 1702 m a.s.l. The lower fronts of these bodies reach 1500-1490 m a.s.l. They are fringed with extensive protalus ramparts, entirely devoid of lichens, indicating quite recent exposure (Fig. 8). For geology and modern treelines, see Tempelglaciären (2).
5. Ekorrglaciären (62°59´N, 12°13´E) is exposed towards south and fills up the inner part of a cirque valley beneath the summit of Mt. Storsola, 1710 m a.s.l. (Fig. 9). By 1908, Enquist (1910) found two minor glaciers here. The smallest one (western) vanished in the 1960s (Lundqvist 1969) and is currently replaced by a rapidly disintegrating ice patch. Repeat photography in 2003 of a view captured in 1922 by Nordhagen (1928) revealed substantial frontal retraction of the remaining glacier (Kullman 2004a, 2007b). Ground studies indicate that its lower margin has moved upslope from 1200 to 1380 m a.s.l. since the early 20th century. For geology and modern treelines see Tempelglaciären (2).

3.2 Tärna

The forefields of two small glaciers were investigated within this area: Tärnaglaciären (6) and Östra Syterglaciären (7):

6. Tärnaglaciären (65°51´N; 15°16´E) is a nisch/valley glacier facing SE in the slope of Mt. Murtsertjåkke, 1644 m a.s.l. (Fig. 10). The lower glacier front is at 1240 m a.s.l. and below there is a large and rapidly disintegrating icefield, extending down to 1075 m a.s.l. The geological substrate is composed of softer schists with amphibolites. The size of the glacier is 0.25 km². The glacier was investigated 1896, 1897 and 1908 by Gavelin (1910). From the published photographs, captured at these occasions, it appears that the glacier has made a substantial upslope withdrawal (c. 160 m) to the present position. Comparing a photograph by Lindgren & Strömgren (2001) with the situation prevailing in 2010, reveals perceivable glacier thinning as well as diminuation and frontal retraction of the icefield over the past decade (Fig. 10). The nearest treelines (2010) for mountain birch, pine and spruce are located, 800, 690 and 710 m a.s.l., respectively.

Figure 6: Aerial view of Storsylglaciären (3). By the early 20th century, the glacier terminated at the small inlet delta by the proglacial lake (Syltjärnen) in the foreground, 1276 m a.s.l. 2005-08-15.

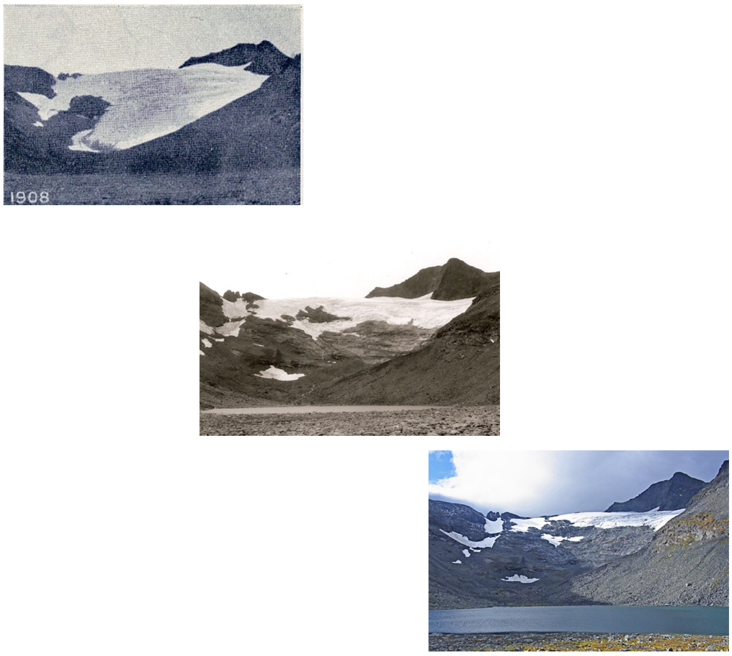

Figure 7: Left-above. Storsylglaciären (3) close to its Neoglacial maximum, in 1908. Photo: Enquist (1910). Mid. By the early 21st century, the glacier had lost approx. 50 % of its prior volume. 2001-08-21. Right-below. Recession has continued during the first decade of the 21st century. 2010-09-10.

Figure 8: Left. Lillsylen (4) from the east. 2009-09-15. Right. The lower front of the ice patch (1500 m a.s.l.) and the fringing protalus rampart. 2002-07-21.

ISSN 1865-1542

Figure 9: Ekorrglaciären (5) from the south. The lowest point is behind a frontal moraine, which has dammed up a small and recently drained lake. 2010-09-10.

7. Östra Syterglaciären (65°54´N; 15°17´E). This glacier, with an eastern aspect, is situated in a broad cirque belonging to Mt. Muortetjåkke, 1586 m a.s.l. (Fig. 11). Today, the lower glacier front terminates in a proglacial lake, 1190 m a.s.l. The glacier size is 0.5 km^2. Based on historical records and photographs (Gavelin 1910), it appears that the elevation of the glacier front is virtually the same as a century ago, although, substantial horizontal retreat is obvious. The small lake and adjacent ground, which were previously covered by glacier ice, are currently ice free (cf. Lindgren & Strömgren 2000). For geology and modern treelines see Tärnaglaciären (6).

3.3 Abisko

This main study area comprises tree glaciers and three snow/ice patches: Kårsajökeln (8), Slåttatjåkka (9, two objects), Kärkerieppeglaciären (10), Kåppasglaciären (11), Låktatjåkka (12).

8. Kårsajökeln (68°18´N, 18°20´E) is characterized as an east-facing mountain side glacier, located on the slopes of Mt. Kårsatjåkka (Fig. 12). This is certainly one of the most thoroughly investigated glaciers in the Swedish Scandes, with respect to Holocene and recent history (Svenonius 1910; Ahlmann & Tryselius 1929; Ahlman & Lindblad 1940; Karlén et al. 1995; Snowball & Sandgren 1996). Aside of some controversy concerning its Holocene glacier history, it is clear from these sources that the lower terminus of the glacier has made a major retraction during the past century. The front has moved upslope from 810 to 965 m a.s.l. and the size has diminished from about 2 to 1 km^2. A broad forefield, about 1 km in length has been freed from ice. The bedrock is dominated by mica schists and some marble beds. The closest treelines (2010) for mountain birch and pine are located 850 and 520 m a.s.l., respectively.

9. Slåttatjåkka (68°21´N; 18°42´E) refers to two large E-facing snow/ice patches within the slopes of Mt. Slåttatjåkka (Fig. 13), 1190, and 1025 m a.s.l., respectively. Both of these objects, with a size of 0.05 and 0.1 km^2, respectively, are fringed with extensive zones of block pavement, totally devoid of higher

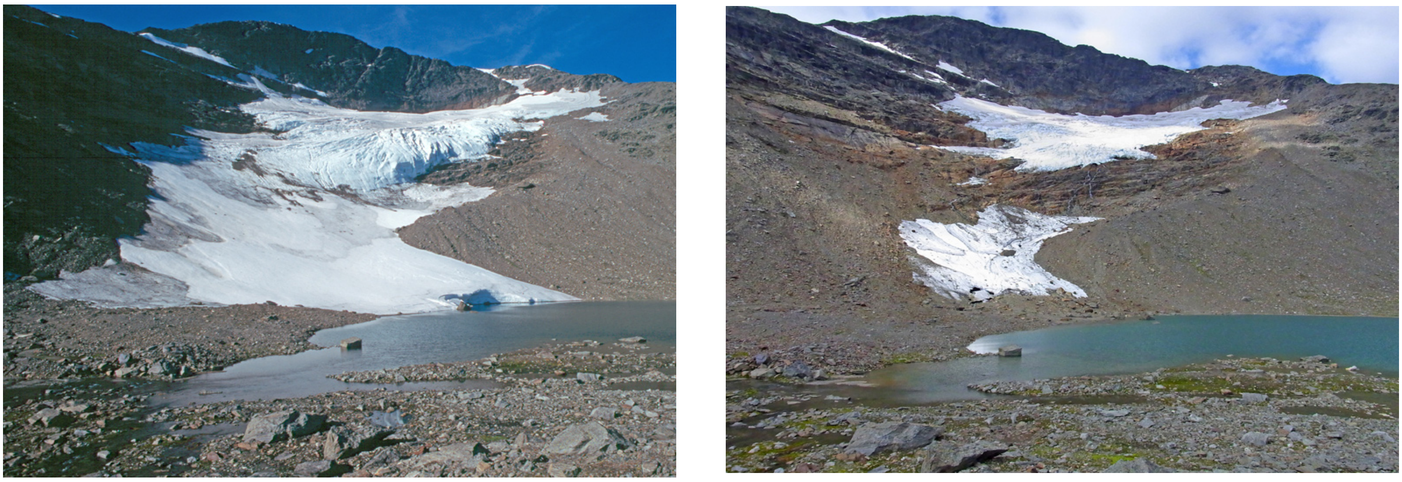

Figure 10: Left. Tärnaglaciären (6) from southeast. The lower glacier front is halfway between the lake and the summit. Below, an extensive snow/ice patch extends virtually down to the lake. Photo: 1999-09-08 (Lindgren & Strömgren 2001). Right. Since 1999, the glacier and the snow/ice patch have receded and thinned substantially. 2010-08-20.

Figure 11: The lower front of Östra Syterglaciären (7). Upslope parts are disguised in clouds. 2010-08-21.

Figure 12: Kårsajökeln (12) and its extensive forefield, which has become freed of ice during the past century. 2009-08-21.

vegetation, mosses and lichens, indicative of recent size reduction of previously permanent snow and ice (cf. Nyberg & Lindh 1990). For bedrock and current treeline positions, see Kårsajökeln (8).

- 10. Kärkerieppeglaciären (68°23´N; 18°18´E) occupies a NE-facing cirque, below the summit of Mt.Vassitjåkka, 1491 m a.s.l. The size is c. 0.5 km^2 (Fig. 14). Drawing on repeat photography, it is clear that the lower front of the glacier has retracted substantially to its current position (1075 m a.s.l.) since the early 20th century (Rapp 1996). For bedrock, see Kårsajökeln (8). The closest treelines (2010) for mountain birch and pine are located, 600 and 375 m a.s.l., respectively.
- 11. Kåppasglaciären (68°22´N; 18°35´E) has an easterly aspect in the lower part of a steep slope below an unnamed summit (1297 m a.s.l.). The size of this glacier is about 0.1 km^2 (Fig. 15). Some frontal recession relative to 1910-20 has occurred, although mainly prior to the 1940s (Lindh 1984). A larger extension of the glacier in the recent past is indicated also by a lichen-free boulder pavement zone, partly covered with "snowbed loess". The lowest glacier front is at 1030 m a.s.l. (2010), to be compared with 1020 m a.s.l. in the early 1980s (Lindh 1984). For bedrock, see Kårsajökeln (8). The closest treelines (2010) for mountain birch and pine are located 870 and 400 m a.s.l., respectively.
- 12. Låktatjåkka (68°23´N; 18°32´E) is an icefield, located on the ESE-facing slope of Mt. Låktatjåkka (1404 m a.s.l.). Currently the size is about 0.1 km^2 (Fig. 16), but an extensive and lichen-free stone pavement zone at the lower front (975 m a.s.l.) signifies a former larger extension. For bedrock, see Kårsajökeln (8). The closest treelines (2010) for mountain birch and pine are located 680 and 400 m a.s.l., respectively.

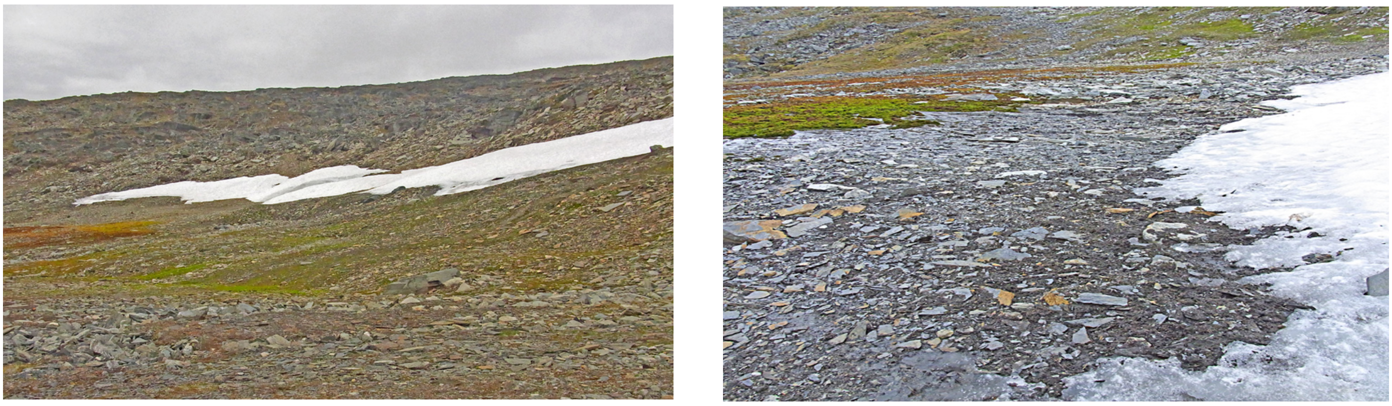

Figure 13: Left. Slåttatjåkka snow/ice patch (9), 1190 m a.s.l. 2010-08-29. Right. Slåttatjåkka snow/ice patch, 1025 m a.s.l. 2010-08-27.

ISSN 1865-1542

Figure 14: Kärkerieppeglaciären (10) with E-facing aspect. 2010-08-27.

Figure 15: Kåppasglaciären (11) with its steep east-facing front. 2010-08-28.

Figure 16: Låktatjåkka snow/ice patch (12). 2010-08-30.

Results

4.1 Subfossil wood remnants

A data set of 78 radiocarbon-dated subfossil tree remants from all three main study areas constitutes the core of this study (Table 1). Of these 56 were determined as birch (*Betula pubescens* sensu lato) and 22 as pine (*Pinus sylvestris*). They were all recovered within the forefields and near the current fronts of receding glaciers and snow/ice patches. Quite frequently, they were closely associated with the main outwash meltwater streams from beneath the ice and snow bodies, and apparently they have been released from the ice and exposed to the free air in very recent time (Fig. 17-19).

Typically, samples were quite small (< 1 m in length), although most likely representing tree-sized specimens. With one exception (Fig. 20), they all had the character of detrital wood, i.e. not rooted in situ. Supposedly they are emplaced from further upvalley growth sites and repositories under the ice. Thus, in most cases, the elevation (m a.s.l.) of the wood remnants has a minimum character, owing to various agents and forces of downslope transport from higher elevations (cf. Kullman 2004b).

A few samples were partly embedded in glaciofluvial deposits or snow patch loess (Fig. 21, 22). Many were badly decomposed, water-soaked and very fragile. However, a few trunk remnants were astonishingly well preserved, with intact bark and small twigs and roots (Fig. 23). Certain specimens were truffled with pebbles, pressed into the wood, indicating strong pressure under the ice (Fig. 24).

Subfossil wood, released from the ice, decomposes very rapidly, once liberated from the ice and subjected to freezing/thawing during a few years (cf. Luckman 1993; Dixon et al. 2005). For example, a large subfossil birch trunk exposed in 2001 (Kullman 2004b, Fig. 8), was virtually totally decayed by 2006. Reasonably, the megafossils are now exposed for the first time since the death of the trees. Repeated observations show that new specimens are washed out each year.

Overall, the sampled megafossils of birch and pine are spread over the time period 13 145 to 4400 cal. yr BP.

During the early Holocene both species attained positions almost 600 m above their respective current treelines (Table 1). A more detailed account of the results is given below for each of the sub-sampling sites.

Aside of the wood remnants, several strongly compressed "peat cakes", containing a rich flora of macrofossils (e.g. *Betula pubescens*, *B. nana*, *Vaccinium uliginosum*, *Empetrum hermaphroditum*) were outwashed on the investigated forefields. Funding restrictions allowed radiocarbon dating of just a few samples.

Large expanses of the commonly windswept landscape at adjacent and higher elevations than the megafossil sites were intensively searched for the presence of subfossil tree remains. The result was entirely negative.

4.2 Helags/Sylarna

One pine sample, originating from the lower front of an ice patch, dates to the Late-glacial period, 13145 cal. yr BP (Fig. 25), as previously reported by Kullman & Kjällgren (2000). Thereafter, no subfossils occur until about 9600 cal. yr BP, when massive appearance of birch and some pine stands out from the megafossil record (Fig. 26). During a subsequent millennium or so, birch exclusively attained elevations almost 600 m above its current treeline, with pine stopping 150 m or more below. Since 9600 cal. yr BP, the upper limit of birch remnants descends gradually by about 300 m until 5600 cal. yr BP, which dates the most recent specimen recovered. No pine sample was younger than 6990 cal. yr BP, when pine appeared 115 and 220 m above the present-day treelines of birch and pine, respectively. Notably, an elevational dip in the upper level of megafossils (birch and pine) is evident for the interval 8400-8000 cal. yr BP. Some samples from this region are shown in Figures 27-29.

4.3 Tärna

The record from this area is quite small and restricted to a narrow elevational interval in the forefileds substantially below the fronts of two glaciers. Pine dominates the early Holocene sample, approx. 9500 to 8000 cal. yr BP and about 270 m above the modern birch treeline (Fig. 30). A single birch sample dated about 9000 cal. yr BP and appeared almost 400 m above the actual treeline. After 8000 cal. yr BP, birch preponderates the record with the youngest age about 4500 cal. yr BP and pine disappearing more than 1000 years earlier. A piece of peat (Fig. 31) recovered right at the front of Tärnaglaciären dated 3890 cal. yr BP (Beta-268552). Figures 32-34 depict some of the megafossils dated in this area.

4.4 Abisko

The dates from this area originate from sites spread over a relatively broad elevational interval. In parallel to the Helags/Sylarna area, a late-glacial/early Holocene pine sample, 12 760 cal. yr BP, is followed by a gap in the record until about 9500 cal. yr BP. Subsequently and until about 7000 cal. yr BP, birch and pine megafossils occur in roughly equal proportions and predominantly within an interval 100-200 m above the modern treeline (Fig. 35). Thereafter, only birch remnants have been found, with the youngest sample 4400 cal. yr BP. Birch peaked during this period, nearly 400 m above today´s treeline position. In this area, an in situ stump of birch was found at the forefield of the Låktatjåkka ice patch (Fig. 20). A chunk of peat delivered by a melt water stream in front of Kårsajökeln (Fig. 36) yielded a date of 3285 cal. yr BP (Beta-268656). Selected samples of subfossil tree remnants derived from glaciers and snow/ice patches in this area are provided by Figures 37-41.

4.5 Composite sample (all study areas)

All three study areas display similar response pattern to modern climate change and share the same broad temporal outlines of the megafossil record, although with different numbers of dated megafossils. Emerging discrepancies in the relative minimum altitudes of the sampled wood remnants, e.g. between Figure 26 and 35, may relate to different strengts of downslope transport and/or birch treelines which have moved upslope more or less close to the glacier front during the past century. With these circumstances taken into account, it may be motivated for a deeper understanding to merge all dates (Fig. 42). We assume that this compilation is broadly representative for the entire Swedish Scandes and we will base the discussion on this data set. The temporally incomplete character of the basic data precludes a more rigorous statistical analysis.

Table 1: Radiocarbon dates of megafossil tree remains retrieved from the forefields of glaciers and snow/ice patches in the three main study areas. “Rel. alt.” means altitude relative to present day treeline. Foot notes 1 and 2 refer to Kullman & Kjällgren (2000) and Kullman (2004), respectively.

Site no.	Coordinates		Rel. Alt.	Altitude	Species	Lab. Code	Radiocarbon age	Calibrated 1δ age range	Intercept value	Sample size (cm)
	N	E	(m)	(ma.s.l.)			(^{14}C yr BP)	(cal. yr BP)	(cal. yr BP)	length x diameter
1A	6254427	1227713	450	1405	Betula	Beta-230895	6950±70	7850-7690	7790	35 x 6
1B	6254446	1228167	395	1350	Betula	Beta-230892	8510±70	9540-9480	9520	20 x 10
1C	6254451	1228176	390	1345	Betula	Beta-230888	8100±70	9090-8990	9020	23 x 11
1D	6254458	1228174	390	1345	Betula	Beta-230889	7860±70	8730-8580	8620	13 x 8
1E	6254395	1227734	465	1420	Betula	Beta-250907	6450±60	7490-7420	7440	13 x 6
1F	6254435	1228168	390	1345	Betula	Beta-284470	6840±60	7700-7620	7670	18 x 7
1G	6254683	1228314	275	1230	Pinus	Beta-250908	7830±60	8640-8550	8600	15 x 7
1H	6254920	1229108	195	1150	Pinus	Beta-127894[1]	11 160±80	13 165-13 030	13 145	35 x 10
1I	6254782	1228452	115	1070	Pinus	Beta-264396	6120±60	7150-6920	6990	12 x 7
2A	6300108	1214281	500	1415	Betula	Beta-230887	8300±60	9420-9250	9300	38 x 9
2B	6300109	1214265	500	1415	Betula	Beta-230890	8170±60	9250-9020	9090	42 x 10
2C	6300264	1214648	415	1330	Betula	Beta-230893	8470±60	9530-9460	9490	38 x 8
2D	6300271	1214654	415	1330	Betula	Beta-230894	8040±60	9020-8800	9000	42 x 9
2E	6300308	1214631	425	1340	Betula	Beta-172306[2]	7630±70	8440-8380	8400	38 x 9
2F	6300260	1214669	415	1330	Betula	Beta-172307[2]	7970±50	9000-8710	8870	40 x 7
2G	6300312	1214627	425	1340	Betula	Beta-172308[2]	7570±50	8400-8350	8380	39 x 7
3A	6301451	1212589	435	1350	Betula	Beta-206075	8620±60	9580-9530	9550	16 x 5
3B	6301530	1212846	365	1280	Betula	Beta-264393	5310±70	6200-5990	6100	15 x 5
3C	6301532	1212925	360	1275	Betula	Beta-172309[2]	7180±60	8020-7950	7970	22 x 6
3D	6301502	1212954	360	1275	Betula	Beta-160105[2]	6220±80	7250-7000	7170	55 x 11
4A	6301841	1212254	585	1500	Betula	Beta-172310[2]	8150±60	9140-9020	9040	18 x 7
4B	6302107	1213049	585	1500	Betula	Beta-172311[2]	8710±60	9740-9560	9680	8 x 5
4C	6302089	1231201	575	1490	Betula	Beta-172312[2]	8430±70	9510-9420	9480	12 x 6
4D	6302076	1231209	575	1490	Betula	Beta-172313[2]	8030±60	9020-8790	9000	10 x 5
4E	6302082	1231287	575	1490	Betula	Beta-172315[2]	7840±70	8660-8550	8610	14 x 7
5A	6259853	1213525	480	1395	Betula	Beta-250915	8290±60	9420-9250	9290	13 x 6
5B	6259851	1213501	435	1350	Betula	Beta-250920	5660±50	6740-6640	6670	23 x 6
5C	6259850	1213505	435	1350	Betula	Beta-250921	8130±70	9130-9000	9020	31 x 19
5D	6259846	1213509	430	1345	Betula	Beta-184489	7920±80	8990-8610	8710	32 x 13
5E	6259824	1213514	405	1320	Betula	Beta-250911	6240±60	7250-7040	7170	16 x 8
5F	6259778	1213594	360	1275	Betula	Beta-250918	6620±50	7570-7460	7500	33 x 9
5G	6259749	1213581	345	1260	Betula	Beta-250919	8160±60	9200-9020	9060	11 x 5
5H	6259682	1213645	335	1250	Betula	Beta-250912	7930±70	8980-8620	8730	33 x 6
5I	6259708	1213651	350	1265	Betula	Beta-284452	4870±60	5650-5590	5600	11 x 4
5J	6259869	1213480	425	1340	Betula	Beta-284468	6220±60	7240-7020	7160	10 x 6
5K	6259854	1213503	435	1350	Pinus	Beta-250922	8060±80	9030-8800	9000	13 x 4
5L	6259804	1213558	400	1315	Pinus	Beta-284451	6740±60	7660-7570	7590	50 x 19
5M	6259711	1213512	325	1240	Pinus	Beta-230896	7390±70	8320-8170	8190	19 x 6
5N	6259559	1213771	295	1210	Pinus	Beta-250913	8530±60	9540-9490	9530	41 x 7
6A	6550945	1516728	270	1070	Betula	Beta-284450	5430±60	6290-6190	6280	18 x 7
6B	6558916	1516681	270	1070	Betula	Beta-284449	4850±50	5610-5580	5590	20 x 8
6C	6550945	1516661	270	1070	Betula	Beta-284455	5240±50	6100-5930	5990	5 x 4
6D	6550910	1516734	265	1065	Betula	Beta-268653	5880±60	6750-6650	6680	17 x 7
6E	6550913	1516724	260	1060	Betula	Beta-268654	6220±60	7240-7020	7160	19 x 8
6F	6550875	1517653	225	1025	Betula	Beta-264395	5990±70	6920-6740	6820	13 x 6
6G	6550927	1516654	275	1075	Betula	Beta-284467	4020±50	4530-4420	4480	15 x 7
6H	6550896	1516761	270	1070	Betula	Beta-284447	4950±50	5730-5610	5660	30 x 11
6I	6550824	1516843	285	1085	Pinus	Beta-284448	8110±40	9030-9010	9020	50 x 12
6J	6550937	1516648	270	1070	Pinus	Beta-284453	5110±50	5920-5760	5900	10 x 3
6K	6550950	1516700	260	1060	Pinus	Beta-284454	7330±60	8190-8040	8170	45 x 14
6L	6550947	1516834	270	1070	Pinus	Beta-264394	8520±70	9540-9480	9530	35 x 10
6M	6550913	1516724	265	1065	Pinus	Beta-268655	7600±60	8420-8370	8400	40 x 11
7A	6553748	1516984	390	1190	Betula	Beta-284469	8080±70	9030-8990	9010	29 x 6
8A	6821610	1821096	80	930	Betula	Beta- 250909	6130±60	7160-6940	7000	40 x 7
8B	6821726	1820156	130	980	Betula	Beta-250917	7920±50	8960-8630	8710	60 x 9
8C	6821744	1819853	140	990	Betula	Beta-264383	8160±90	9260-9010	9060	30 x 12
8D	6821731	1820152	135	985	Betula	Beta-264385	7250±60	8160-8000	8030	18 x 7
8E	6821628	1820292	165	965	Betula	Beta-264386	8290±70	9420-9140	9290	20 x 8
8F	6821744	1819885	155	955	Pinus	Beta-250906	10 130±60	11980-11680	11760	30 x 8
8G	6821771	1819969	140	940	Pinus	Beta-250914	8270±60	9400-9130	9280	30 x 12
8H	6821735	1819882	190	990	Pinus	Beta-264384	5980±50	6890-6740	6790	40 x 15
8I	6821629	1820316	150	950	Pinus	Beta-264387	6130±60	7160-6940	7000	7 x 4
8J	6821657	1820531	145	945	Pinus	Beta-264388	8250±60	9380-9120	9260	15 x 5
9A	6821886	1841110	175	1025	Betula	Beta-284457	4760±50	5590-5460	5530	45 x 7
9B	6821930	1841297	165	1015	Betula	Beta-284458	6900±60	7790-7670	7700	13 x 6
9C	6821891	1841131	180	1030	Betula	Beta-264392	8210±70	9290-9030	9130	30 x 8
9D	6821888	1841128	180	1030	Betula	Beta-264391	8510±70	9540-9480	9520	31 x 5
9E	6821887	1841126	180	1030	Pinus	Beta-264390	8380±80	9480-9300	9440	14 x 7
9F	6821861	1841293	155	1005	Pinus	Beta-284456	7690±50	8540-8420	8450	53 x 10
9G	6821474	1841305	240	1090	Pinus	Beta-284461	7710±70	8570-8420	8490	40 x 10
10A	6823189	1818025	370	1050	Betula	Beta-284459	6090±60	7140-6890	6950	18 x 7
10B	6823099	1817956	380	1060	Betula	Beta-284460	4600±50	5440-5300	5310	17 x 6
11A	6821807	1834763	155	1025	Betula	Beta-284462	6100±60	7150-6900	6980	50 x 12
11B	6821833	1834819	145	1015	Betula	Beta-284463	3900±60	4420-4240	4400	12 x 5
11C	6821841	1834883	145	1015	Betula	Beta-284465	4270±50	4860-4830	4840	13 x 6
11D	6821808	1824764	160	1030	Pinus	Beta-284464	6870±60	7750-7660	7680	30 x 10
12A	6824603	1832415	295	975	Betula	Beta-284472	5040±60	5900-5710	5800	18 x 8
12B	6824590	1832372	300	980	Pinus	Beta-284471	8020±70	9010-8770	8990	36 x 10

Except for the late-glacial presence of pine both in the north and the south, a striking feature emerging from Figure 42 is the sharp early clustering of birch and pine around 9600-9500 cal. yr BP, with birch reaching more than 100 m higher than pine. This spatial pattern remains over the entire period embraced by both birch and pine megafossils, i.e. until about 5900 cal. yr BP, when pine disappears from the record. During a millennium or so after 9500 cal. yr BP, birch subfossils emerged nearly 600 m higher than the 2010 treeline positions. In parallel to a long-term consistent descent of the upper subfossil birch limit since about 8500 cal. yr BP, the relative proportions of birch increase substantially until the youngest end of the range of the birch record, about 4400 cal. yr BP. The somewhat fortuitous record implies that this pattern should be interpreted cautiously. As indicated by a few dated peat samples, the inception of glacier ice may have post-dated the discontinuation of the birch record by at least 1000 years or so.

A noteworthy aspect of the record is an elevational decrease by about 150 m, embracing the interval 8400-8000 cal. yr BP.

Figure 18: Kåppasglaciären (11). Wood remnant of pine, exposed right at the glacier front. 7680 cal. yr BP (Beta-284464).

Figure 17: Kåppasglaciären (11). Recently outwashed birch log. 6980 cal. yr BP (Beta-284462).

Figure 19: Tärnaglaciären (6). Large piece of a birch stem with bark fragments, exposed in the main drainage stream. 6280 cal. yr BP (Beta-284450).

Figure 20: Låktatjåkka (12). Basal part of a small birch tree, obviously preserved in situ. 5800 cal. yr BP (Beta-284472).

Figure 21: Slåttatjåkka (9). Wood pieces of birch in a thick layer of snow patch loess. 9130 cal. yr BP (Beta 264392).

Figure 22: Slåttatjåkka (9). Fragment of pine wood, exposed close to Figure 21. 9440 cal. yr (Beta-264390).

Figure 23: Kårsajökeln (8). Basal birch trunk with intact bark and remnants of twigs, exposed close to the glacier front. 8710 cal. yr BP (Beta-250917).

Figure 24: Ekorrglaciären (5). Piece of a pine trunk, with small pebbles pressed into the wood (right). 7590 cal. yr BP (Beta-284451).

Figure 25: Helagsglaciären (1). Subfossil remnants of pine, dating to the Late Glacial, recovered in the lower reaches of the glacier forefield.
13 145 cal. yr BP (Beta-127894).

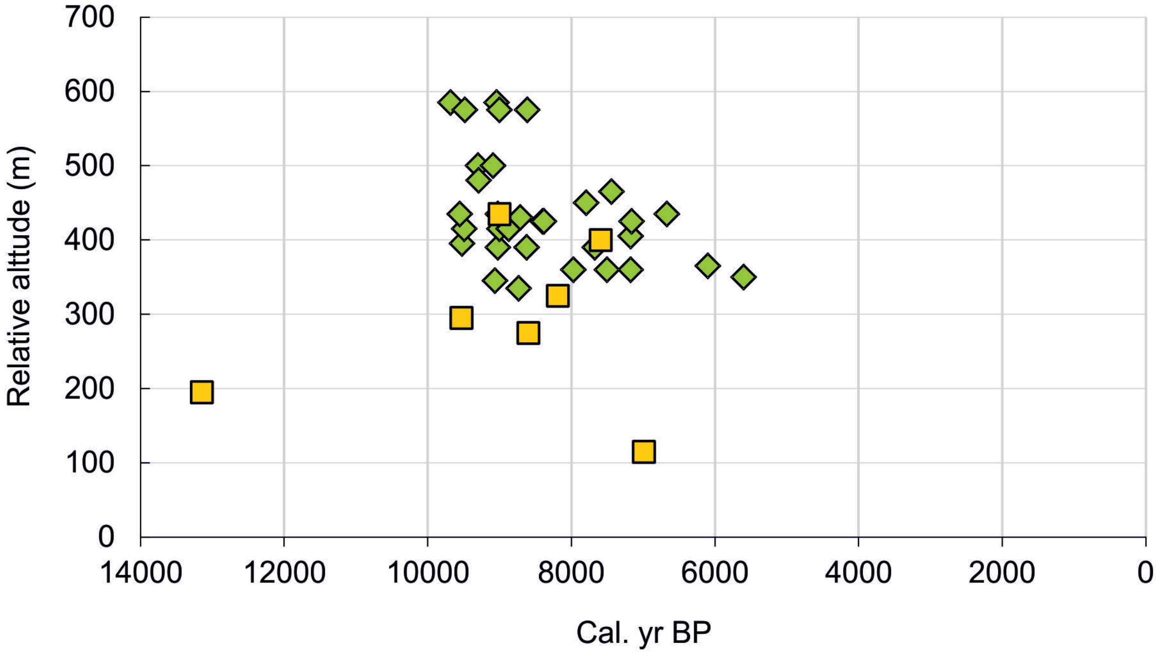

Figure 26: Radiocarbon dates of birch (green) and pine (yellow) megafossils, relative to the present day position of the birch treeline (zero). Helags/Sylarna (1-5).

Figure 27: Helagsglaciären (1). Part of a birch stem preserved by outwash sediments in the lower part of the forefield. 7790 cal. yr BP (Beta-230895).

Figure 28: Ekorrglaciären (5). A piece of pine wood exposed in the lower part of the forefield and clearly not in situ. 9530 cal. yr BP (Beta-250913).

Figure 29: Ekorrglaciären (5). Left. A chunk of bark from a fairly stout birch tree, exposed in a drainage strem. 9020 cal. yr BP (Beta-250921). Right. Close-up view.

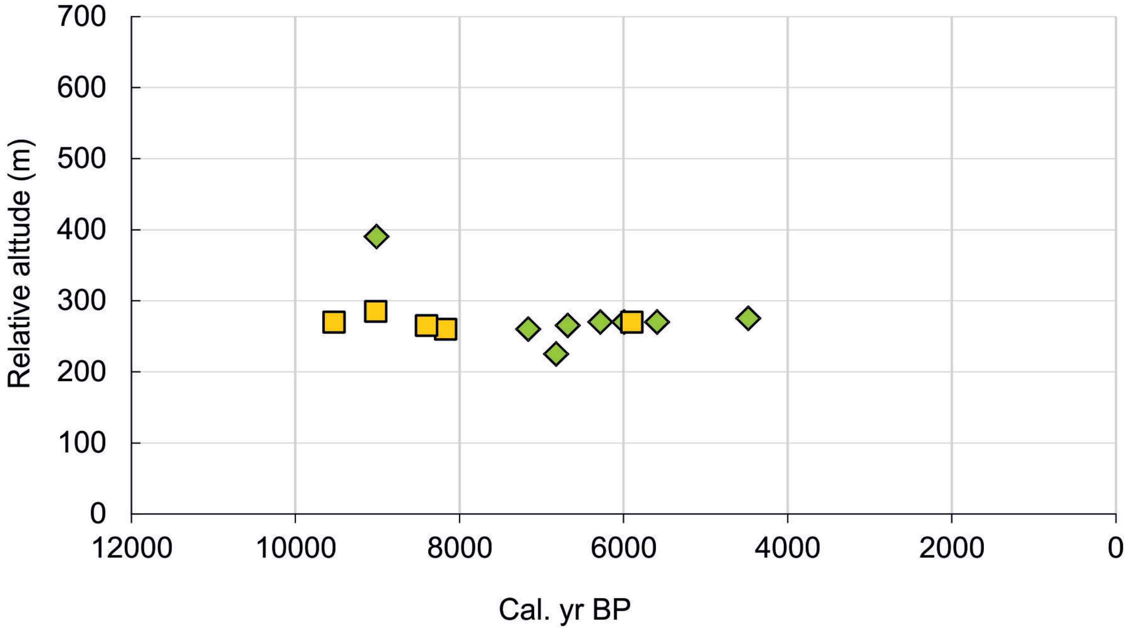

Figure 30: Radiocarbon dates of birch (green) and pine (yellow) megafossils, relative to the present-day position of the birch treeline (zero). Tärna (6-7).

4.6 Recent treeline change in the Abisko-area

Estimates of elevational birch treeline changes were carried out at six localities (defined sections of specific mountain slopes) within the Abisko-area (Table 2). This sub-study covers the period from the early-1950s to 2010. All investigated sites have experienced a substantial upshift of the treeline over the past 60 years, ranging between 105 and 225 m. About half of this advance took place after 1972. In many cases it appears from the individual growth forms, e.g. polycormic modes with stools of decaying stem remains that the new treeline markers have existed as low-growing, multi-stemmed shrubs for long periods until they quite recently attained tree size. That inference is supported by observations made during the 1930s of 0.5 m high birch shrubs growing at the same elevations as the recently attained treeline position (Sandberg 1940, 1963). Thus, treeline rise is predomintly accomplished by growth form change of old-established krummholz to erect tree forms.

Overall, the results obtained in the Abisko-region concur with the outcome of analogous studies carried out in more southerly parts of the Swedish Scandes (Kullman & Öberg 2009). This large-scale response pattern stresses the pivotal role of climate warming as the main driver (cf. Sandberg 1940, 1963; Holmgren & Tjus 1996) and questions the decisive role of strictly local and heterogeneous impacts, e.g. reindeer grazing, as claimed by Van Bogaert et al. (2011). The maximum treeline rise by 225 m since the 1950s is a record breaking value for the entire Scandes (Fig. 43), indeed a reasonable response since warming in this area appears to have been somewhat larger than further south in the Scandes (Callaghan et al. 2010). Possibly, the upslope shift since the early 20th century may be even larger at some localites, since some advance was observed to have taken place in this area prior to the 1950s (Sandberg 1940, 1963; Ahlmann 1953).

The structure of the pine treeline is impacted by fire and logging prior to the 20th century and by intensive browsing by moose (*Alces alces*) during the past few decades. In addition, regeneration and upslope advance is hampered by luxuriant birch forest above the pine treeline. Nevertheless, the pine treeline on the S-facing slope of Mt. Slåttatjåkka has shifted upslope by 45 m to 520 m a.s.l. during the past decade.

Figure 31: Tärnaglaciären (6). Strongly compressed peat, outwashed by a meltwater stream. 3890 cal. yr BP (Beta-268552).

Figure 32: Tärnaglaciären (6). A large pine remnant recovered in the forefield, which has been deglacited during the past century. 9530 cal. yr BP (Beta-264394).

Figure 33: Tärnaglaciären (6). Piece of a small subfossil birch stem, obviously displaced to this site quite recently. 6680 cal. yr BP (Beta-268653).

Figure 34: Tärnaglaciären (6). Unmistakable pine remnant, reasonably displaced by snow and water from a location higher upslope. 9020 cal. yr BP (Beta-284448).

Table 2: Treeline positions (m a.s.l.) and elevational change (m) at six different localities in the Abisko area, as recorded in 1950, 1972 and 2010, respectively.

Locality	N lat.	E long.	Aspect	1950	1972	2010	Change 1950-2010
Kuoblatjårro	6821482	1824553	S	735	no record	850	115
Tjatjenjåskatjåkka	6820740	1837956	S	740	800	860	120
Slåttatjåkka 1	6821383	1843651	SE	675	760	850	175
Slåttatjåkka 2	6820972	1842488	E	665	730	815	150
Kåppasåive	6822028	1838623	ESE	645	730	870	225
Björkliden, peak 883	6824447	1838020	E	575	605	680	105

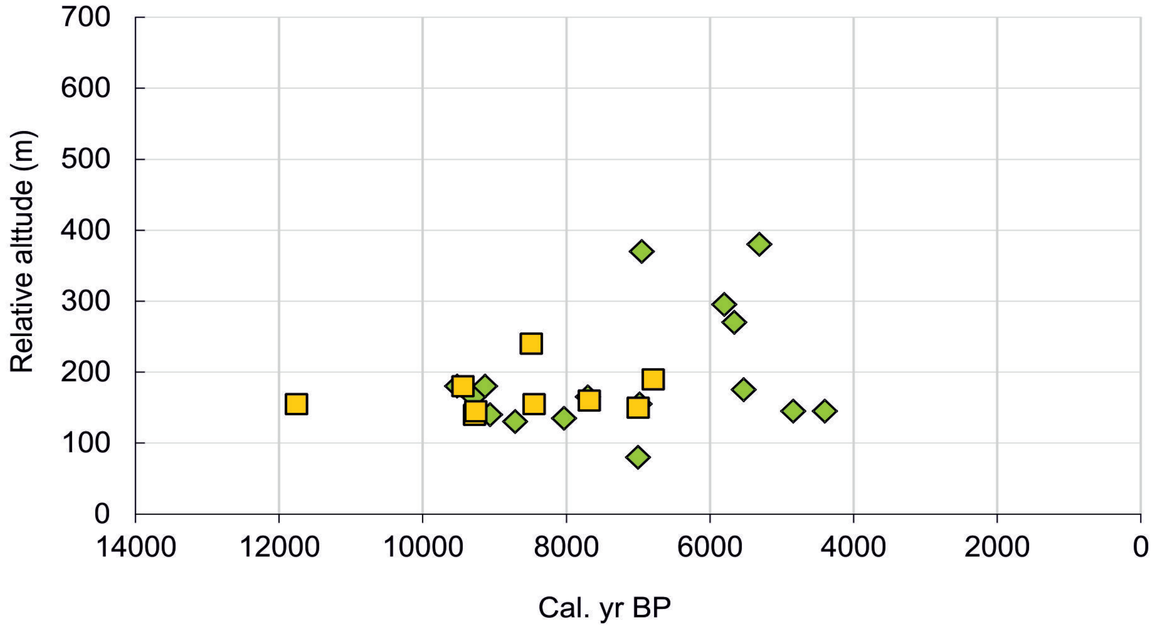

Figure 35: Radiocarbon dates of birch (green) and pine (yellow) megafossils, relative to the present-day position of the birch treeline (zero). Abisko (8-12).

Figure 36: Kårsajökeln (8). Compressed peat cake, 3285 cal. yr BP (Beta-268656), with an attached birch twig (not dated), drifting in a melt water stream.

Figure 37: Kårsajökeln (8). Lower part of a small pine tree, with some roots preserved. Recently outwashed from beneath the glacier. 6790 cal. yr BP (Beta-264384).

Figure 38: Kårsajökeln (8). Piece of a subfossil pine (upraised), unearthed from water-eroded outwash material. 11760 cal. yr BP (Beta-250906).

Figure 39: Slåttatjåkka (9). Birch stem recently exposed by the main outwash stream of the ice patch (1025 ma s.l.). 530 cal. yr BP (Beta- 284457).

Figure 40: Slåttatjåkka (9). Pine wood remnant appearing in a "channel" opened in the snow/ice patch (1090 m a.s.l.). 8490 cal. yr BP (Beta-284461).

Figure 41: Kärkerieppeglaciären (10). Parts of a birch stem with large bark fragments preserved. 5310 cal. yr BP (Beta-284460).

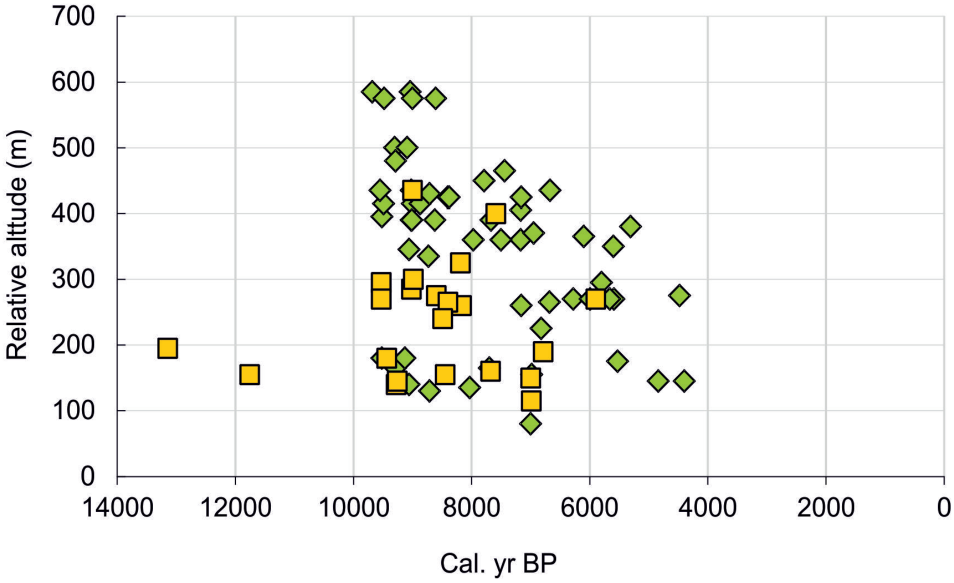

Figure 42: Composite sample of all radiocarbon-dated megafossil birches (green) and pines (yellow), relative to the present position of the birch treeline. Helags/Sylarna, Tärna and Abisko (1-12).

Figure 43: The current (2010) birch treeline in Kåppas Valley (870 m a.s.l.), about 3 km northeast of Kåppas-glaciären.

Discussion

It is startling to witness that high-alpine sites in the Scandes, 500-600 m above the contemporary treeline and currently occupied by glacier ice and perennial snow, have for long periods of the early- to mid- Holocene harboured stands of trees. What is more, this appears as a fairly regular pattern along the Swedish Scandes, which emphatically highlights the huge climatic span between the early and late part of an interglacial epoch. It is particularly noteworthy also that ancient megafossil wood is being released also from beneath relatively small snow/ice patches.

Absence of megafossils on forefields situated higher than those investigated here, in combination with the long-term lowering of the upper birch megafossil limit, suggest that the study has actually captured the treeline. This inference is supported by the fact that earlier studies, reporting megafossil birches, at lower alpine elevations, do not show this gradual depression (Aas & Faarlund 1988, 2000; Kullman 1995).

A particularly noteworthy aspect of this study is that from the Late Glacial to the present day, the treeline history appears to be virtually the same along most of the Scandes (but see e.g. Berglund et al. 1998). This suggests a common climatic cause as the main driver of Holocene treeline performance.

5.1 Vegetation history

The study corroborates the much debated view (e.g. Birks et al. 2006; Kullman 2006) that different boreal tree taxa, in this case pine, colonized ice free high mountain areas (nunataks) in Scandinavia already during the Late-Glacial (cf. Kullman 2002b, 2008; Paus et al. 2011). During the Late Glacial/Holocene transition, i.e. the gap period in the present megafosil record, birch, pine and spruce existed in low abundance and frequency at particularly favourable microhabitats elsewhere in the high mountains (cf. Kullman 2002b, 2008; Paus et al. 2011). The swift and massive emergence of megafossils at the last-mentioned point of time is understandable only with the nearby existence of such early "infection nodes" also in the study area. Whether the concerned glaciers existed or not during the interval between the Late Glacial and 9500 cal. yr BP cannot be judged from the present data.

In contrast to earlier studies (Karlén 1976; Berglund et al. 1996; Barnekow 1999; Rosén et al. 2001; Seppä et al. 2004a; Bigler et al. 2002), the new data from the Abisko-region, in combination with an earlier case study (Kullman 1999), provide clear evidence that pine immigrated to this region much earlier and to substantially higher maximum elevations than commonly inferred by more conventional paleoecological approaches. Furthermore, the present study suggests that pine was a more frequent constituent of the early Holocene tree flora at high elevations than previously assumed (e.g. Barnekow 1999; Bigler et al. 2002; Seppä et al. 2004b).

Aside of the sparse late-glacial records, the data obtained in the present study indicate a widespread and first massive tree stand establishment phase shortly prior to 9600 cal. yr BP along the entire Swedish Scandes. This pattern is broadly consistent with inferences based on pollen and megafossils retrieved also from other parts of the Scandes (Dahl & Nesje 1996; Aas & Faarlund 2000; Barnett et al. 2001; Eide et. al 2005; Bergman et al. 2005; Kullman & Kjällgren 2006; Paus 2010; Paus et al. 2011; Öberg & Kullman 2011). Early-Holocene tree growth of birch and pine up to 600 m above the current treelines of these species is a finding, which provides a new view on the structure of the early-Holocene high-mountain landscape. The existence of solely birch megafossils 100-150 m above the upper range limit of scattered pine remnants suggests that, strictly locally, birch grew as discrete stands or solitary trees well above a more or less continuous belt of pine or mixed pine/birch throughout the period embraced by the megafossils.

Neither this nor prior studies (Kullman 1991, 1995, 2004b; Kullman & Kjällgren 2006; Paus 2010) could find megafossils of any species outside and at equally high or higher altitudes than the uppermost investigated glacier/snow patch forefields. Prima facies, this could imply that trees never grew there. This assumption gains some support from the fact that the recent treeline rise of birch is thwarted in these topoclimatic settings, where wind seems to effectively unable tree growth, irrespective of temperature (Kullman & Öberg 2009; Leonelli et al. 2011). On the other hand, it cannot be entirely ruled out that the reason for absence of positive evidence is that prevailing preservation conditions (small lakes thin raw humus and peat accumulations) are less conducive in these settings. However, quite large bark fragments of *Betula nana* were frequent in thin raw humus and peat packs at these elevations. Thus, also *Betula pubescens* whould have been analogously represented under similar circumstances, given factual presence. On the balance of evidence, we hypothesize that the highest early Holocene tree growth was exclusively accomplished by birch and confined to sheltered localities of the kind, which harboured glacier and snow patches during the late Holocene. This view is corroborated by macrofossil evidence suggesting that large expanses of the present-day open alpine landscape has been unforested throughout much of the Holocene (Seppä et al 2004b; Öberg & Kullman 2011). However, more definite conclusions in these respects have to await more intense and focused studies.


Figure 44: Subfossil pine unearthed by recent wind erosion in a snow poor high alpine environment. 10 350 cal. yr BP (Beta-184490). The site Mt. Getryggen, 1250 m a.s.l., is located 18 km northeast of Storsylglaciären (3) and 500 m above the present-day pine treeline.

At somewhat lower elevations, however, glacier/snow accumulating sites supported both birch and pine. In addition pine, but not birch, grew in dry and exposed sites over a wider spectrum of the landscape (Kullman & Kjällgren 2006) (Fig. 44).

The details and further evolution (posterior to 4400 cal. yr BP) of a birch forest belt as we know it today is beyond the power of the present study. We speculate, however, that in response to late-Holocene Neoglacial cooling, birches growing within the postulated pockets were exterminated by progressive snow and ice growth. Eventually, local climate conditions previously restricted to the “pocket sites” became regionally ubiquitous over the mountain landscape, which paved the way for the emergence of subalpine birch forest as a broad-scale landscape unit.

It may seem paradoxically that empty glacier cirques and nivation hollows should have been particularly apt for the highest and uppermost first postglacial tree

Figure 45: The empty glacier cirque of Mt. Lillstensdalsfjället. Dense birch stands and some pines prevail in the lower slopes, while scattered trees prosper at favourable spots at much higher elevations, above the scree slopes. This may be an analogue of the situation in many cirques where subfossil wood is witness of early-Holocene tree growth. 2010-09-13.

stand vegetation in the high mountains, leaving the major part of the surrounding high-alpine landscape untreed. However, it is recognized that in the absence of ice and snow, habitats of this kind may offer quite favourable environmental conditions for plant growth (cf. Elven 1978, 1980; Scherrer & Körner 2011).

The more or less parabolic, steep and often dark backwalls of many cirques may optimize radiation heating. Wind shelter, ample snow cover/soil moisture and a complex microtopography (ledges, crevices, boulders) accentuate the favourable premises. In addition, these often rugged and boulder-strewn slopes offer safe sites, protected from snow avalanches.

Further support for the congenial nature of the concerned habitat type is that alpine plant species enrichment and upslope migration of "forest plants" in response to the modern warming phase are particularly perceivable in these settings. Despite the relative high elevation of all investigated megafossil sites, young and vigorous saplings of birch, pine and spruce are found here, 400-600 m above current treelines, and in higher frequency than outside at similar elevations (cf. Kullman 2001b, 2004b, 2010b). The same phenomenon of sapling enrichment in glacier forefields is encountered in different parts of the world (e.g. Olsson 1967; Holtmeier 1974).

Wind-driven snow accumulation is a prerequiste for the initiation and persistence of these intermittent glacier and snow/ice bodies (Lundqvist 1969), which have hidden early-Holocene tree stands until the present day. By the same agent, seeds and other propagule are selectively enriched in these habitats (cf. Kullman 1984, 2004a), and consequently, during intervals of climate warming a fairly rich plant cover may arise.

An illustrative idea of the general character of an early Holocene cirque with a "birch pocket" is provided by the present situation at Mt. Lillstensdalsfjället, 18 km NE of the study area Helagsfjället/Sylarna (Öberg 2010). Here, a wide cirque is occupied by closed birch forest stands in the lower slopes, while scattered trees and the treeline are located much higher upslope. Although, mainly facing north, the curvature of the cirque implies that the westernmost slopes receive a lot of sun radiation during the warmest part of the day.

Under these circumstances, the treeline of birch attains one of the highest positions in the region (1070 m a.s.l.) and also displays nearly the largest upshift (190 m) during the relatively warm 20th century (Kullman & Öberg 2009) (Fig. 45). Furthermore, at one of the studies sites (Tempelglaciären), a 1.5 m high and multi-stemmed rowan (*Sorbus aucuparia*) grows on a cliff ledge at 1600 m a.s.l. (Fig. 46), which is about 700 m higher than its local treeline. Many alpine vascular plant species display their highest stations in the entire Swedish Scandes in these slopes (Kilander 1955).

Outlying, azonal occurrences of spruce are occasionally found in similar cliff wall habitats (Kullman 2010a). One example is the clonal spruce “Old Molly”, prospering in splendid isolation in the steep south-facing slope of Mt. Åreskutan, where it appears to have existed throughout the past 6400 years, at least (Öberg 2010). Apparently, it is no coincidence that the first recorded late-glacial trees (megafossils) in the Scandes were found in this type of environment (Kullman 2002b).

Figure 46: Tempelglaciären (2). Shrubby rowan (*Sorbus aucuparia*) growing in a favourable local climate on a cliff ledge at the backwall of the glacier cirque.

5.2 Paleoclimate

Both treeline and glacier dynamics are recognized as robust and high-confident proxies for summer temperature, showing virtually the same trends (Broecker 2001; Holtmeier 2003; Körner 2007; Nicolussi et al. 2005; Holmlund et al. 2005; Menounos et al. 2009). Despite their discontinuous and somewhat fortuitous nature, these sources seem to allow more straightforward interpretations than other frequently used biological climate proxies (diatoms, chironomids, pollen), which are beset with major uncertainties and inter-study disparities, particularly during the early Holocene (e.g. Barnekow 1999; Rosén et al. 2001; Velle et al. 2005a; Bigler et al. 2006). In this context it should be considered that paleotreeline dates, based on megafossils, are first-hand evidence. Most other paleoclimatic proxies are more indirect and inferential to their nature.

Given the tight and overlapping assemblage of tree megafossils between 9600 and 4400 cal. yr BP (Fig. 42), it appears quite safe to infer that studied glaciers and snow/ice patches, as well as others, did not exist during that time span. This general interpretation conflicts with some prior studies based on various proxies (e.g. Karlen et al. 1995; Hormes et al. 2001), but is largely in line with glacier histories from other parts of Scandinavia (Snowball & Sandgren 1996; Rosqvist et al. 2004; Bakke et al. 2005; Nesje 2009) and fit with a world-wide pattern of minimum glacier extent (even absence) and volume during the early-to mid-Holocene (e.g. Baroni & Orombelli 1996; Hormes et al. 2001; Beierle et al. 2003; Levy et al. 2004; Nicolussi et al. 2005; Thompson et al. 2006; Menounos et al. 2009; Buffen et al. 2009; Briner et al. 2010). In many of the cases cited above, the paleorecord displays minor sub-millennial scale glacier volume fluctuations during the Holocene. The methodology of this study does not possess the time-resolution necessary to address this issue. The only indication in that way is the gap in the record about 8000-8400 cal. yr BP. This feature may signify a secular-scale regression event of tree growth, possibly in response to increasing permanency of snow and perhaps some minor glacerization. Notably, a distinct hemispheric cold event and associated plant cover responses is discerned within the last-mentioned interval (cf. von Grafenstein et al. 1998; Nesje & Dahl 2001; Barnett et al. 2001; Kobashi et al. 2007; Paus 2010; Paus et al. 2011; Öberg & Kullman 2011).

Megafossil-evidenced tree growth about 400-600 m higher upslope than at present, and the concurrent absence of many glaciers, clearly sustain that the postglacial thermal and seasonality maximum, coupled with relatively dry conditions, was during the earliest part of the Holocene (cf. Kullman & Kjällgren 2000, 2006; Korhola et al. 2002; Bigler et al. 2003; Hammarlund et al. 2004; Velle et al. 2005b; Nesje et al. 2006; Paus et al. 2006; Shakesby et al. 2007). Unadjusted for glacio-isostatic land uplift and assuming a temperature lapse rate of -0.6 °C per 100 m altitude (Laaksonen 1976), summers may have been 3.5 °C warmer than in the early-21st century. This is more than inferred by some other proxies in northern Fennoscandia (e.g. Barnekow 1999, Seppä & Birks 2001; Bigler et al. 2002), but quite close to other estimates (e.g. Aas & Faarlund 1988; Moe 1994; Shemesh et al 2001; Bigler et al. 2003; Bjune et al. 2005; Kullman & Kjällgren 2006; Paus 2010; Paus et al. 2011). The discrepancy between inferred temperatures by the present and earlier studies is understandable primarily in terms of the exceptionally high relative tree growth positions displayed at the glacier forefields. For more, this is a minimum estimate, since at least some of the megafossils are likely to originate from growth sites higher upslope than the forefields from where they were retrieved (cf. Kullman 2004b). The timing of the 3.5 °C temperature anomaly is consistent with a general model based on the Earth´s orbital parameters, forcing a northern hemisphere summer insolation maximum (COHMAP members 1988; Berger & Loutre 1991).

A temperature 3.5 °C higher than currently, implies that the early Holocene landscape and its biotic structure may hold some clues as to hypothetical model predictions for an alleged future "greenhouse world" (IPCC 2007), although it should be recognized that many boundary conditions differ between then and now. It needs to be stressed also that quantitative temperature reconstructions, drawing on past treeline positions, may be biased since climate-treeline relations are quite complex, including aspects of both summer and winter temperatures, precipitation and wind, all agents operating directly and in poorly understood feed back systems (Hammarlund et al. 2004; Holtmeier & Broll 2005, 2007; Paus 2010; Kullman 2010a).

The gradual altitudinal lowering of the upper limit of megafossil dates and their absence from the record after ~4400 cal. yr BP is likely to be an expression of progressive Neoglaciation. Drawing on the last megafossil date of each study area, the timing of the final stage of this process, i.e. the demise of trees seems to differ somewhat from site to site between 5600 and 4400 cal. yr BP.

This model is consistent with several studies indicating a stepwise transition to a predominantly more unfavourable climate for tree growth and a more favourable climate for glaciers at and after this interval (cf. Karlén 1976; Caseldine & Matthews 1987; Berglund et al. 1996; Snowball & Sandgren 1996; Kullman 2003; Rosqvist et al. 2004, Bakke et al. 2008; Velle et al. 2005b; Hammarlund et al. 2004; Bergman et al. 2005; Paus 2010).

Absence of tree megafossils dating to the past 4400 years indicates that a major part of this period has been substantially colder and/or more snow rich than the interval 9600 to 4400 cal. yr BP, when trees flourished within the habitats later on filled with ice and snow. Based on a few peat samples, post-dating the final disappearance of trees, we hypothesize that glacier ice reformed 3900-3300 cal. yr BP. In one case, Kårsajökeln, this figure is in close accord with results from sedimentological studies in proglacial lakes within the same area (Snowball & Sandgren 1996).

To put recent glacier disintegration and driving climate warming during the past century into a long-term (Holocene) context is not an entirely unambiguous task. Provided that the megafossils had been preserved and exposed in situ, it would have been straightforward to infer that recent warming, which exposed the megafossils, was unique for the past 4400 years. However, all samples from glacier forefields are outwash detrital wood, which might be released more or less continuously, without any relation to recent glacier recession. Lack of prior observations of this kind of remnants in glacier environments, intensively researched over many decades (for other purposes), argues against this possibility. This view gains further support from the fact that megafossils with similar ages as those exposed just outside the glacier fronts are melted out also from relatively small and thin snow/ice patches (cf. Kullman 2002b). Since these are situated in relatively flat terrain without high "overlooking" backwalls, recent emergence is likely to be in near-in situ positions. In fact, one sample was clearly preserved right at the growing place (Fig. 20). Reasonably, ice/snow features of this kind should be more vulnerable than glaciers to minor and short-term warming episodes of modern dimensions (Nyberg & Lindh 1990; Farnell et al. 2004), which would cause rapid and complete decay of the megafossil record. Balancing these arguments, we find it likely and hypothesize that the emergence of a rich sample of detrital wood is a consequence of recent climate warming, possibly unsurpassed during the past 4400 years or so. This hypothesis comply with prior studies of past and present pine treeline evolution within the concerned areas (Kullman 2003; Kullman & Kjällgren 2006; Kullman & Öberg 2009), and from various proxies elsewhere in the Scandes (Velle et al. 2005b; Bakke et al. 2008) and in other parts of the world (Haeberli & Bensiton 1998; Grosjean et al. 2007; Kaufman et al. 2009; Buffen et al. 2009). Lack of tree growth in the forefields and at similar elevations outside these habiats indicate that temperatures are still lower than prior to 4400 cal. yr BP.

By using the present results as a tentative paleoanalogue for future treeline evolution, it appears that secular warming by 3-3.5 °C, as often anticipated from climate models, may force treelines upslope by 500-600 m in elevatation. Hypothetically, this will not occur on a broad front over the present-day alpine landscape. Much like recent climate-driven treeline advance (Kullman & Öberg 2009), this putative process will take advantage of sheltered sites where late-laying snow and ice have precluded tree growth for long times in the past. A more conclusive basis for these projections can only be achieved by continued monitoring of actual treeline performance.

Conclusions

1. Abundant megafossil tree remains of *Betula pubescens* ssp *czerepanovii* and *Pinus sylvestris* are found at the forefields of rapidly disintegrating mountain glaciers and snow/ice patches along the Swedish Scandes. The upper limit of these sites is 400 to 600 m above current treelines.
2. Radiocarbon dating revealed presence of *Pinus* already during the late glacial period. The bulk of megafossils (*Betula* and *Pinus*) range between 9600 and 4400 cal. yr BP, indicating a period of uninterrupted tree growth at sites covered by glacier ice and perennial snow during the late-Holocene, until the onset of widespread glacier recession about a century ago. No ancient wood remnants could be found outside and at similar elevations as the investigated habitats.
3. *Betula* constituted the upper 100-150 m of the entire set of dated megafossils. At lower elevations, mixed occurrences of *Pinus* and *Betula* remnants prevailed throughout the period represented by megafossils within the focused habitat types. This pattern is interpreted as a reflection of the actual tree species zonation.
4. Tree growth 600 m above current treeline position during the early Holocene implies that summer temperatures may have reached 3.5 °C above the early 21st century levels. Monotonous descent of the upper subfossil limit indicates gradual lowering of the local treelines driven predominantly by orbitally forced neoglacial cooling. This process culminated with the extirpation of tree stands and their replacement with glacial ice and perennial snow over the past 4400 years.
5. Climate warming during the past 100 years or so, i.e. the likely prerequisite for emergence of megafossils, is discussed in a longer term context. It is tentatively suggested that warming of the magnitude and duration, characteristic of the past 100 years or so, has not occurred after the discontinuation of the megafossil record.
6. Forefields of glaciers/ice patches constitute a new and promising avenue of high-alpine paleoecology in the Swedish Scandes. Rapid disintegration of exposed subfossil material urges for immediate and multi-disciplinary action to secure the unique information contained herein.

Acknowledgements

Financial support for this study was provided by the Swedish Research Council (to Leif Kullman), and by Jämtland County Administrative Board and Mid Sweden University (to Lisa Öberg). We are greatful to prof. Bengt-Gunnar Jonsson and two anonymous reviewers for valuable comments on the manuscript.

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