Shrinking glaciers and ice patches disclose megafossil trees and provide a vision of the Late-glacial and Early post-glacial subalpine/alpine landscape in the Swedish Scandes – review and perspective

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Abstract

Extensive glacier recession has prevailed for almost 100 years in the Scandes and other parts of the world. At the lower fringe and forefields of shrinking alpine glaciers and ice patches, a plethora of ancient tree remnants is recovered. This is presumably the first time of exposure since burial by ice thousands of years ago. These remains represent prior stands of virtually all boreal tree species, currently growing in northern Scandinavia. As a consequence, a previously unexpected and patchily treed high-mountain landscape emerges, in some cases 600-700 m higher than present-day treelines. This difference in treeline positions between then and now (corrected for land uplift) indicates that summer temperatures have declined by about 3 °C since the early Holocene treeline maximum. Radiocarbon-dating reveals that the age of the tree remnants ranges between c. 16,800 and 2000 cal. yr BP. Initially, the high-mountain peaks stood out as nunataks in a surrounding for long glaciated landscape at lower elevations. As the ice sheet gradually shrunk, glacier cirques and hollows became filled with tree groves, in a matrix of alpine tundra. In addition to *Betula pubescens* ssp. *czerepanovii*, *Picea abies* and *Pinus sylvestris*, these high-elevation enclaves contained tree species, previously unknown to such high positions and so early. These are *Picea abies* and a species currently considered as exotic to Scandinavia, namely *Larix sibirica*. In response to gradual climate cooling since the middle Holocene, the tree stands declined and dead trees were eventually entombed by glacier ice, which is currently disintegrating.

Keywords: Glacier recession, climate change, treeline ecotone, megafossils, Holocene, Swedish Scandes

Introduction

The structure and plant species composition of Late-glacial and Early-Holocene landscapes in the Swedish Scandes are poorly comprehended. In this respect, traditional pollenanalytical inferences, glacier histories and textbook narratives are beset with inaccuracies and uncertainties, particularly in high-mountain regions (e.g. Lundqvist 1969; Huntley & Birks 1983; Berglund et al. 1996; Karlén & Kuylenstierna 1996; Barnekow 1999; Johnsen 2010). These methodological shortcomings are evidenced by analyses of more direct, robust and reliable mega- and macrofossil records (cf. Helama et al. 2004; Paus 2013; Paus & Haugland 2017; Kullman 2017a). Unambiguously, these approaches are stating formerearly local presence of tree species at specific sites and elevations, far beyond modern treelines.

Megafoossil1 tree remains, representing former higher-than-present alpine treelines, mainly preserved in peat and lake mud, have for long been known and discussed in the Scandes. These records have contributed broad outlines of the Holocene history of high mountain landscape and climate evolution (Smith 1920; Lundqvist 1969; Karlén 1976; Kullman 1995; Aas & Faarlund 2000; Kullman & Jägglgren 2000, 2006). However, studies of this kind are constrained by sparseness of peat as an efficient preservation medium at high elevations, which has urged for alternative megafossil archives when searching for the highest positions of tree growth during earlier epochs.

1Megafoossils are large pieces of wood, which are preserved near their growth places and which can be accurately determined to species and dated by the 14C-method. Ages are reported as calendar years BP (AD 1950), by intercept-values, and derive from sources, cited above.
Megafossil records, originating from different elevations above the modern treeline, have displayed a discernible trend of treeline lowering throughout the Holocene, about 50 m per millennium (Kullman 1995; Kullman & Kjällgren 2000), in broad agreement with orbital forcing of insolation at the top of the atmosphere (Berger & Loutre 1991). Since this mechanism suggested a thermal maximum somewhat prior to the earliest and highest existing records, further search for megafossil wood remnants was extended to even higher elevations.

Particular focus was on the fringes of currently melting glaciers and snow/ice patches along the entire Swedish Scandes (Fig. 1). In addition, these efforts were inspired by positive results, based on megafossils, from emerging proglacial sites worldwide, showing that forest trees had prevailed at sites until recently covered by ice, during earlier parts of the Holocene, (Nicolussi & Patzelt 2000; Schlüchter & Jörin 2004; Benedict et al. 2008; Ivy-Ochs et al. 2009; Koch et al. 2014). Prior to the studies reviewed in this study, no such discoveries had been reported from the Scandes.

Results of these recent investigations, carried out in different parts of the Swedish Scandes, constitute the main core of this paper. The present review upsets the traditional comprehension of the late-glacial and early postglacial climate as well as the structure and composition of the high-elevation landscape (cf. Paus 2013; Kullman 2013; Luoto et al. 2014; Välimäki et al. 2015; Schenk et al. 2018). Possibly, the emerging views may serve as proxy analogues of future subalpine landscapes in a potentially warmer world. In fact, the initial phase of such a course of change may be already underway in the Swedish Scandes (Kullman 2010, 2019). However, such projections should be treated cautiously, since future directions of the climate evolution remain uncertain.

![Figure 1. Subfossil pine, which inspired search for megafossils at exceptionally high elevations, particularly on the forefields of receding glaciers. The lower fringe of the glacier “Sylglaciären”, 1195 m a.s.l., about 400 m higher than the present treeline. Radiocarbon yielded 10,425 cal. yr BP. Photo: 1997-07-16. Source: Kullman & Kjällgren 2000.](image)

**Results**

**Late-Glacial and early-Holocene trees as evidenced by megafossils—the new landscape perspective**

All main tree species of the current treeline ecotone were present on what has to be interpreted as ice-free nunataks (Fig. 2-5) already at the Late-Glacial/Early-Holocene transition, 17 000–13 000 years before the present day (BP) at unprecedented high elevations along the entire Swedish Scandes (Kullman & Kjällgren 2000; Kullman 2002, 2004). These species are mountain birch (*Betula pubescens* ssp. *czyzowica*), Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). Henceforth, these will be cited as *Betula*, *Picea* and *Pinus*, respectively.

The core site for discovery of the earliest tree megafossils is Mt. Åreskutan (1420 m a.s.l.) in the southern Swedish Scandes (province of Jämtland), 1360 m a.s.l. and 510 m above the treeline of pine. This mountain has, close to its summit, until quite recently, harboured an ice patch or a small glacier, which has gradually vanished in response to 20th century climate warming and consequently megafossil trees have been exposed (Figs. 2 & 3).
Figure 2. Locus classicus, 1360 m a.s.l., the site for the discovery of Late-glacial and Early-Holocene tree presence on early emerging nunataks in the Scandes (Kullman 2002). These findings have changed the conception of the earliest subalpine/alpine landscape-history. a. A small glacier/ice patch prevailed here until quite recently. Its former position is indicated by the snow patch and the row of blocks in the foreground. The snow has completely melted by the end of late summer during most years of the past few decades. Photo: 2018-07-18. b. The former ice-distribution embraced the green moss-covered area in the center. Here, most of the megafossils have been recovered, reasonably dislocated downslope by snow avalanches from higher upslope positions. Photo: 2018-09-01.

Figure 3. Overview of the earliest megafossils recovered at the Åreskutan-site, 1360 m a.s.l. a. Pinus sylvestris, 13 810 cal. yr BP. b. Picea abies, 13 010 cal. yr BP. c. Betula pubescens s.l., 16 810 cal. yr BP. These samples highlight earlier local deglaciation and tree instatement than previously inferred by more traditional approaches. Source: Kullman 2002.

Figure 4. Examples of Late-Glacial megafossil tree recoveries at sites along the entire Swedish Scandes. a. The glacier Helagsglaciären (province of Härjedalen), has receded areally by c. 40% during the past 100 years.
Photo: 2015-08-13. b. Close to its former lower maximum range, 1150 m a.s.l., megafossils of *Pinus* were recovered and dated 13,145 cal. yr BP. Photo: 2008-07-04. Source: Kullman & Kjällgren 2000.c. The glacier Tärneglacären (province of Lapland). Currently, a large snow-field prevails in the mid-slope below the glacier, which extended down to the mid of the lake (1070 m a.s.l.) about 100 years ago (Lindgren & Strömgren 2001). Photo: 2010-08-20. d. Preserved in a downwashed peat-cake 630 m a.s.l., a cone of *Picea* was dated 11,200 cal. yr BP. Photo: 2017-09-01. e. The glacier Kärsaglacären, 965 m a.s.l. (province of Lapland). Photo: 2009-08-21. f. A megafossil remnant of *Pinus* appeared in the outwash stream from beneath the glacier Kårsaglacären, 955 m a.s.l. It dated 11,760 cal. yr BP. Photo: 2008-09-17. Source: Öberg & Kullman 2011.g. Mt. Städjan (province of Dalarna), 1110 m a.s.l. h. Megafossil *Pinus* protruding from a thin soil layer between boulders in the south-facing slope of Mt. Städjan. Dating yielded 12,425 cal. yr BP. Photo: 2007-07-14.

The firm evidence, presented above, conflicts with traditional glacial geologic and paleobotanical opinions and have been questioned and opposed by proponents and defenders of these approaches, drawing on negative evidence (Birks et al. 2005) and refuted by Kullman (2006).

**Holocene megafossils in their settings**

Below, a representative sample of megafossils recovered in geomorphic glacial cirques, with currently receding ice cover, is presented. This is a comprehensive and richly illustrated review of previously published data and updates, representing the Swedish Scandes, from south to north (Öberg & Kullman 2011, Kullman & Öberg 2013, 2015; Kullman 2017a,b) (Figs. 5-20). A popular overview is given by Kullman & Öberg (2019). Surprisingly, little research on these issues has been carried out in Scandinavia by palaeoecologists, although archaeologists, particularly in Norway, are making rich findings of human artifacts on the forefields of melting glaciers and ice patches (e.g. Nesje et al. 2011).

![Figure 5](image1.png)

Figure 5. The position of the glacier sites, particularly focused in this review. 1. Helags-Sylarna glaciers. 2. The glacier Tärneglacären with adjacent ice patches. 3. Glaciers and snow/ice patches in northern Lapland.

1. Helags-Sylarna glaciers

![Figure 6](image2.png)

Figure 6. Downwashed stem of *Betula*, 1345 m a.s.l., which dated 8620 cal. yr BP. Mt. Helagsfjället. Photo: 2010-08-11.
Figure 7. Subfossil Betula, extracted from eroding moss-cover in a downstream proglacial delta below the glacier, 1350 m a.s.l. Dating yielded 9520 cal. yr BP. Mt. Helagsfjället. Photo: 2006-10-15.

Figure 8.a. Remnant of a fairly stout Betula-tree, uplifted from beneath the moss-cover in the delta below Storsylglaciären, 1275 m a.s.l. Presumably, the original growth position was higher upslope. Dating yielded 7170 cal. yr BP. Photo: 2001-08-22.b. A downwashed Pinus-remnant, 1210 m a.s.l., recovered well below its assumed original growth position, underneath the background Ekorrglaciären. Radiocarbon-dating gave 9530 cal.yr BP. Photo: 2008-08-24.
2. The glacier Tärnaglaciären with adjacent ice patches

Figure 9. “High-flying” Betula-megafossil at the margin of an ice-patch adjacent to Tärnaglaciären, 1425 m a.s.l. This is 635 m higher than the current local treeline. Dating yielded 9195 cal. yrBP.Murtsergure ice patch. Photo: 2012-08-28.

Figure 10. Piece of a Betula-stem, recovered 1410 m a.s.l., 700 m higher than the nearest present-day treeline. It is currently being washed downslope from a growth place close to an ice-patch, adjacent to the glacier Tärnaglaciären. It dated 9365 cal. yr BP. Photo: 2017-09-01.
Figure 11. *Betula*-megafossil, protruding from the snow rime at the glacier front, 1395 m a.s.l. This site is 685 m higher than the current local treeline. Dating yielded 9450 cal. yr BP. The glacier Tärnaglaciären. Photo: 2017-09-01.

Figure 12. A virtually new source of past high-mountain vegetation composition is provided by outwashed “peat-balls” of this kind. Here uplifted from behind a stone in the main melt-water stream. Their content of plant remains represents some of the former plant cover composition were ice prevailed until quite recently (see Fig.13). Ice-patch near the glacier Tärna-glaciären, 1115 m a.s.l. Photo: 2012-09-22.
Figure 13. Tree remains of different species contained in “peat balls”, released from beneath glacier ice in the Tärna region (source: Kullman & Öberg 2013). Except for common forest bryophytes and dwarf-shrubs, cones of Larix sibirica and Picea abies as well as leaves of deciduous boreal tree species, have been extracted and radiocarbon-dated; a. Larix sibirica, 7320 cal. yr BP. b. Picea abies, 8450 cal. yr BP. c. Pinus sylvestris, 7960 cal. yr BP. d. Sorbus aucuparia, 8460 cal. yr BP. e. Populus tremula, 8590 cal. yr BP.

3. Glacier and snow/ice patches in northern Lapland

Figure 14. Trunk of Pinus, dug out from glacier sediment, 940 m a.s.l. Obviously, it is worked by beaver (Castor fiber), indicative of a local forest environment at the dated time; 9280 cal. yr BP. The glacier Kårsaglaciären. Photo: 2008-09-17.
Figure 15. Megafossil remains of *Betula*, exposed just outside the lower glacier margin and much higher than the present local treeline, 990 m ö.h. They date 1950 cal. yr BP and support a general conception of a warmer-than-present time, with a smaller glacier (Kullman 2013). The glacier Kårsaglaciiären. Photo: 2013-09-12.

Figure 16.a. The glacierKäppasglaciären, c. 9 km west of Abisko in Swedish Lapland. Today, it should possibly be characterized as an ice-field. It released a megafossil *Pinus* at its lower margin, 1030 m a.s.l.b. Dating yielded 7860 cal. yr BP. Photo: 2010-08-28.
Figure 17. a. An elongated snow/ice patch, located c. 15 km northwest of Abisko, extending 975-980 m a.s.l. At the lower margin, an extensive stone pavement indicates a prior more extensive size of this object. The front is currently disintegrating by “calving”, which exposes new mineral ground with some emerging megafossil tree remains. Photo: 2010-08-30. b. Megafossil Pinus, dated 8900 cal. yr BP, up-raised from original position. Photo: 2010-08-30. c. Basal part of a Betula stem, possibly preserved in situ, 975 m a.s.l. Radiocarbon-dating gave 5800 cal. yr BP. Låktatjåkka Ice Field. Photo: 2010-08-30.
Figure 18. **a.** The glacier Kitteldalsglaciären in the Kebnekaise-massif. The lower front is about 1190 m a.s.l. Megafossils of *Pinus* and *Betula* are recovered along the right-hand (east-facing) margin of the glacier. Photo: 2013-08-11. **b.** *Pinus-*log melting out from the glacier, 1240 m a.s.l. It dated 9010 cal. yr BP and is located 690 m higher than the local present-day treeline. Photo: 2013-08-11.

Figure 19. The glacier Storglaciären in the Kebnekaise-massif is one of the most thoroughly investigated glaciers in the Swedish Scandes, although mainly with respect to size and mass balance changes. About 100 years ago the lower front was close to the lake, c. 1115 m a.s.l. (cf. Holmlund 2012). Photo: 2013-08-13

Figure 20. **a.** Megafossil log of *Betula*, which dated 8490 cal. yr BP, 1100 m a.s.l. Photo: 2013-08-30. **b.** Downwashed peat cake, containing a *Picea* cone shell, 1105 m a.s.l. Photo: 2013-08-13. **c.** A *Picea* coneshell dated 8380 cal. yr BP. The glacier Storglaciären.

**Synthesis and discussion**

Demonstrably, alpine glaciers along the entire Scandes have been melting over much of the past century (Lundqvist 1969; Holmlund et al. 1996, Bakke et al. 2008). At their lower fronts, megafossil tree remnants of different species are currently exposed. Radiocarbon-dated, these samples provide a new view of the Late-Glacial and Early-Holocene high mountain landscape. It now stands out, that along the entire Swedish Scandes, all of our common tree species grew in small isolated populations, much earlier and at higher positions, than ever...
The discussion below draws on an “amalgam” of previously published original studies, based on megafossils retrieved from glacier forefields (Kullman 2004; Öberg & Kullman 2011, Kullman & Öberg 2013, 2015; Kullman 2017a,b). These references provide additional detail and documentation to the images, which make up the core of this paper.

Table 1. For each of the study sites (Fig. 5), age range of all megafossils, given as cal. yr BP, and corresponding relative elevation range of sample sites, displayed as altitudinal meters above the current treeline.

| Site | Age-range   | Relative elevation range |
|------|-------------|--------------------------|
| 1    | 16 810-6100 | 115-585                  |
| 2    | 9530-4480   | 225-700                  |
| 3    | 11 760-1950 | 80-690                   |

A particular noteworthy novelty is that boreal trees grew at sites of present-day glaciers already during the Late-Glacial as early as about 17 000-12 000 years before the present. Analogous inferences are presented from the Norwegian Scandes (Paus et al. 2011). Taken together, these discoveries have a bearing both on glacier and vegetation history. The common wisdom, until present, has been that the high mountains were completely ice-covered at this early stage (Lundqvist 1986, 1994), a view questioned (e.g. by Dahl et al. 1997; Follestad 2003; Hörnberg et al. 2006; Goeringa et al. 2008), and certainly not compatible with the presence of trees, if not assuming supraglacial tree growth. In fact, the last-mentioned option is discussed by different authors (Fickert et al. 2007; Zahle et al. 2018).

The ice-free glacier cirques displayed the character of outlying forest enclaves, high above the closed and continuous forest below. Prior to 10 000 BP, the dated samples are too few to form definite opinions about the relative abundance of Betula, Pinus and Picea in the concerned habitats, although all three species were present at high elevations during that period, as evidenced by this review. Possibly, the contemporary sparsity of recoveries related to still incomplete deglaciation and relatively small areas available for tree growth on the nunataks.

Since about 10 000 years BP, Betula appears to have formed the upper treeline in these habitats, although Pinus is found to have joined Betula at the highest elevations, 600-700 m above current treelines, as these appeared during the past 10 years or so (Kullman & Öberg 2009; Öberg & Kullman 2011). Except for the dominating tree species particularly focused and depicted in this study, the early tree vegetation contained an array of sub-ordinate boreal tree species, which today prevail sparsely in the mountain forest below. These species are Sorbus aucuparia, Alnus incana, and Populus tremula, all documented by megafossils (Kullman & Öberg 2013, 2015).

Presumably, the Late-glacial and Early-Holocene nunatak tree groves may have served as dispersal nodes for trees and other plants, enabling their rapid subsequent downslope spread and establishment over the ice-free landscape as it gradually emerged (cf. Väviranta et al. 2011, 2015).

It is of particular interest to find that Picea sitchensis occurred on a regular basis and at unprecedented high elevations above its current treeline, and so even during the Late-Glacial. This contrasts with the orthodox view (based on pollen analysis) of spruce as a particularly late postglacial immigrant to western and high-elevation Sweden (Moe 1970; Giesecke & Bennett 2004; Seppä et al. 2009). Encouraged by the megafossil evidence presented above, some researchers, drawing on microfossils and DNA-technique, support the option of early Holocene presence of Picea in the high-mountains (Segerström & von Stedingk 2003; Hörnberg et al. 2006; Paus 2010; Paus et al. 2011; Parducci et al. 2012; Carcaill et al. 2012). In addition, during the early Holocene, the concerned tree groves harbored a tree species not growing spontaneously in Sweden today, namely Larix sibirica (Kullman 2018), which also occurred outside the present kind of habitats along the entire Scandes, both in Sweden and Norway (Kullman 1998; Bergman et al. 2004; Paus 2010; Carcaill et al. 2012). Possibly this light-demanding species was outcompeted by advancing denser populations of Betula and Picea by the mid-Holocene, as these species were favored by the evolving Neoglacial climate, which then turned to a more oceanic and snow-rich character (cf. Kullman 2018). By analogy with the rich tree flora, it is reasonable to assume that plant species richness in general was high in these, obviously sparse high-elevation tree stands. This gains support from analyses of plant remains in peat-cakes released from beneath the glacier ice (cf. Kullman & Öberg 2013, 2015). The presence of tree assemblages is suggested also from the fact that beaver (Castor fiber), an obligate forest dweller, utilized trees growing in these sites (Fig. 14).
Tentatively, the maximum difference by 700 m between the early-Holocene treeline position and the present treeline may be translated into summer temperature change decline over this period of time. Based on a general temperature lapse rate of 0.6 °C per 100 m altitude (Laaksonen 1976), it may be inferred that the temperature has lowered by 4.2 °C since 9500 cal. yr ago. However, this figure, has to be adjusted due to the effect of subsequent glacio-isostatic land uplift, which here may be in the order of 200 m (Påsse & Andersson 2005). This reduces the figure on which temperature change may be calculated to 500 m and consequently a temperature 3.0 °C higher than at the present day.

A warmer climate in the future, as commonly alleged, may turn the high mountain landscape into a state envisioned by the findings for the early Holocene, as depicted in this study. Tentatively, this implies a high-mountain landscape, virtually without glaciers and large late-lying snow/ice patches. The former sites of these elements are likely to stand out as isolated treed oases high above the continuous forest. The surrounding more wind-exposed and snow-poor terrain remains virtually untreed, by analogy with the reluctance of trees and forests to colonize this type of habitats in response to the warming of the past 100 years (Kullman & Öberg 2009).

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