



Recent and past arboreal change: Observational and retrospective studies within a subalpine birch-dominated (*Betula pubescens* ssp. *czerepanovii*) mountain valley in the southern Swedish Scandes - responses to climate change and land use

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ABSTRACT

Multi-scale observations and reconstructions of treeline and associated plant cover changes are reviewed in this study. The main focus is on the dynamics of the treeline ecotone within a mountain valley in the southern Swedish Scandes. This area is well-researched for more than 100 years, with a background of historical studies covering the entire Holocene epoch. Trees were present on ice-free nunataks already during the Late-Glacial, 17 000-13 000 cal. a BP. Mountain birch (*Betula pubescens* ssp. *czerepanovii*), Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) then grew 400-700 m higher than their current treelines, indicative of summer temperatures 3 °C higher than present. In addition, the tree flora contained Siberian larch (*Larix sibirica*) and broad-leaf thermophilic and deciduous species, *Quercus robur*, *Corylus avellana*, *Ulmus glabra* and *Alnus glutinosa*. Eventually, the climate turned cooler, particularly enhanced around 5000 cal. a BP. This course of change initiated the Neoglacial period, when thermophilic species were extirpated. Concomitantly, mountain birch forest and spruce benefitted from this course of change. Pine, on the other hand was disfavored and regressed in the treeline elevation and general abundance on the landscape. These trends continued until the Mediaeval period AD 1000-1300, when temperature raised above present-day standards and the pine treeline locally shifted upslope by at least 100 m. This favourable epoch was discontinued quite abruptly by resurgence of Neoglacial cooling; the “Little Ice Age”, which prevailed until the late 19th century. Widespread glacier expansion, high-elevation arboreal decline and treeline retraction then occurred. With a gentle onset in the late 19th century or somewhat earlier, a modern and still prevailing warming period was accentuated by the late 1930s. Subsequently, slight cooling prevailed for 3-4 decades, whereupon warming was resumed with short interruptions until the present day. One distinct short-term cooling-conditioned setback occurred during the 1980s. Transient permafrost formed close to the treeline, and locally some treeline recession took place. Thereafter, warming has re-occurred and glaciers and permafrost have receded. Treeline rise and densification of the treeline ecotone are once again active processes in the mountainscape. Currently, most conspicuous is a process of pine reclamation of local ground lost during the Little Ice Age. Hereabouts, seed

regeneration, still virtually without winter injuries, is taking place at an unprecedented rate and abundance. Mountain birch is gaining ground in snow rich depressions in the birch belt and is currently regressing in exposed and snow-poor sections of the local topography. Current biotic changes within the treeline ecotone are well within the ranges of inferred natural variability during the postglacial period.

Key words: Treeline ecotone, climate change, human impact, biodiversity, subalpine/alpine landscape transformation, Swedish Scandes

INTRODUCTION

The widespread societal concern and anxiety about proposed future anthropogenic climate change and its ecological consequences (IPCC 2013; Pierrehumbert 2019) need to be viewed in a robust historical context. In a total Holocene perspective, climate change has been the norm and its modern evolution and drivers should be evaluated accordingly (Vinós 2022). Cold-marginal tree growth constitutes an ideal object of study and consideration in that respect (Körner 2021; Vinós 2022). More specifically, it is generally approved that the history and dynamics of the alpine and arctic treeline ecotones, at population and landscape levels, reflect recent and past climate change and variability in interaction with local drivers and circumstances, eg. topoclimate, herbivory and land use (Payette et al. 1985; Brubaker 1986; Kullman 1998a; Holtmeier 2009; Kullman & Öberg 2009). Preferably, repeated present-day *in-situ* records, combined with megafossil historical inferences, can provide this perspective in a proper way.

Megafossils are well-preserved ancient wood remnants (trunks, roots and branches), retrieved from peat deposits or margin of melting glaciers, and dated by the ^{14}C -method. This approach constitutes the most accurate way to pin-point the presence of a certain tree species and indirectly glacier ice in space and time (Elven et al. 2013; Odland 2021).

Henceforth, the *treeline ecotone* is taken as the transition zone between the *treeline* and the elusive upper rim of closed forest, the so-called *forest-limit*. The treeline of a given species is by convention narrowly defined as the altitude (m a.s.l.) of the uppermost individual, at least 2 m tall (Miehe & Miehe 2000). This is the only measure that provides stringent and spatially coherent proxy expression of an arboreal climate limit and its dynamics in high-mountain regions (Kullman 2001, 2022a; Nagy 2006). Any arbitrarily defined *forest-limit* has a more noisy character, with little inter-site coherence in the landscape. The treeline, the focal point of this study, appears as a more sensitive and practicable indicator of ecological climate change effects, compared to the forest-limit (Kullman 2022a).

During the past 50 years, the senior author has carried out various studies of treeline dynamics in different parts of the Handölan Valley in the southern Swedish Scandes. This is one of the most well-researched mountain areas in the Swedish Scandes with respect to past and recent arboreal and general vegetation dynamics. The overall objective of this study is to provide a holistic and representative landscape-scale synthesis of observed responses to climate change during the past 100 years or so, in perspective of the entire Holocene period.

STUDY AREA

The study comprises an entire catchment transect, running c. 40x5 km north-south along the Handölan River in the county of Jämtland, southern Swedish Scandes (Fig. 1). The mouth of the valley is close to the village Handöl and Lake Ånnsjön, 526 m a.s.l. (Fig. 2). Since 1967, a small road runs 11 km along the valley floor between Handöl and Storulvån Tourist Station.

The head of the valley is on the high-plateau near Mt. Helagsfjället, 1030 m a.s.l. (Fig. 3). The highest peaks are Mt. Helagsfjället (1796 m a.s.l.) and Mt. Sylarna (1761m a.s.l.) in the southern part. Further north, the surrounding mountains are lower, 1100-1500 m a.s.l.). The bedrock is made up with amphibolites, phyllites and sedimentary gneisses, covered with glacialfluvial and lacustrine sediments. At the surface, peat and podzolic soil prevail over large areas in the valley floor and over the lower slopes (Lundqvist 1969; Borgström 1979a,b).

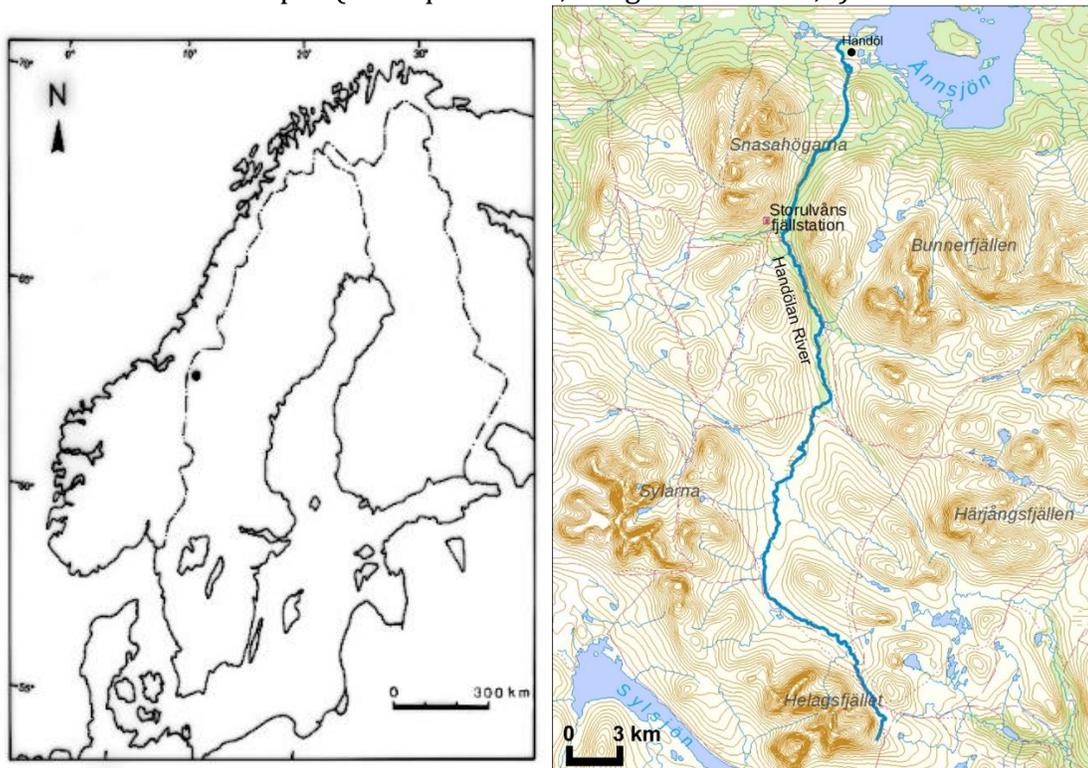


Figure 1. Left. The study area in the southern Swedish Scandes (dot). Right. Detailed map showing the Handölan river valley and adjacent mountains. Excerpt from Fjällkartan 1:100 000, Z6 Storlien-Ljungdalen ©Lantmäteriet (2012/899). Geographic names in the text refer to this map.



Figure 2. An alluvial delta has built up at the mouth of the Handölan River and harbours the small village Handöl, with its roots in the mid-16th century. Former local mining and farming have affected the local landscape by selective felling of pines and spruces, livestock grazing and hay making. The delta forest (in the foreground) is made up predominantly of *Alnus incana* and *Betula pubescens* ssp. *czerepanovii*



Figure 3. This low-alpine landscape of hummocky terrain (900-1000 m a.s.l.), with relative heights of 5-10 m, was clad with tree groves of pine and mountain birch until about 5000 cal. yr BP. The Sylarna massif stands out in the background. Photo: 2015-08-13.

The valley floor and the surrounding lower mountain slopes are covered with an altitudinal belt of mountain birch forest (*Betula pubescens* ssp. *czerepanovii*), which trails off southwards in the valley, to a point about 30 km south of Handöl. Open stands and scattered trees of spruce (*Picea*

abies) and pine (*Pinus sylvestris*) are interspersed within the birch belt over the northernmost 4-5 kilometers of the study transect. A modern vegetation map covers the study area (Rafstedt 1984).

The flora and its elevational differentiation are given by (Kilander 1955). These older records have served as a useful basis for assessment of floristic changes between now and then (Kullman 2007a, b). The entire mountain valley is a Sami cultural landscape, utilized for different kinds of reindeer husbandry for many centuries, which has not perceptibly changed the general structure of the landscape and its basic natural processes.

The climate is weakly maritime; most pronounced in the northern part of the focused transect, as reflected by some plant species with a western affinity, e.g. *Anemone nemorosa*, *Blechnum spicant* and *Narthecium ossifragum* (Fig. 4).



Figure 4. The fern *Blechnum spicant* indicates a weakly oceanic climate in the Handölan Valley. Mt. Storsnasen 620 m a.s.l. Photo: 2022-09-27.

Mean temperatures (1961-1990), recorded at the Storlien/Storvallen meteorological station (595 m a.s.l.) for January, July and the year are -7.6, 10.7 and 1.1 °C, respectively. Over the period 1901-2021, summer (June-August) and winter (December-February) mean temperatures increased by 1.6 and 1.5 °C, respectively (Fig. 5). Centennial climate warming is consistent with multi-species treeline advance, alpine flora enrichment, restructured alpine plant communities, spread of alien plant species, plant phenological change, glacier retreat and vanishing permafrost (Kullman 2007a,b, 2017a,b). These aspects are focused in more detail below.

The animal world species richness in the valley has gained from new species: beaver (*Castor fiber*), roe deer (*Capreolus capreolus*), badger (*Meles meles*). In addition, new birds and butterflies with southern affinities have emerged.

One aspect of climate change, with a clear bearing of climate-driven landscape ecological change is the leafing of the subalpine birch forest and snow melt phenology. At one site in the

study area, the present-day situation (1977-2022) can be assessed in relation to conditions 1914 (Fig. 6).

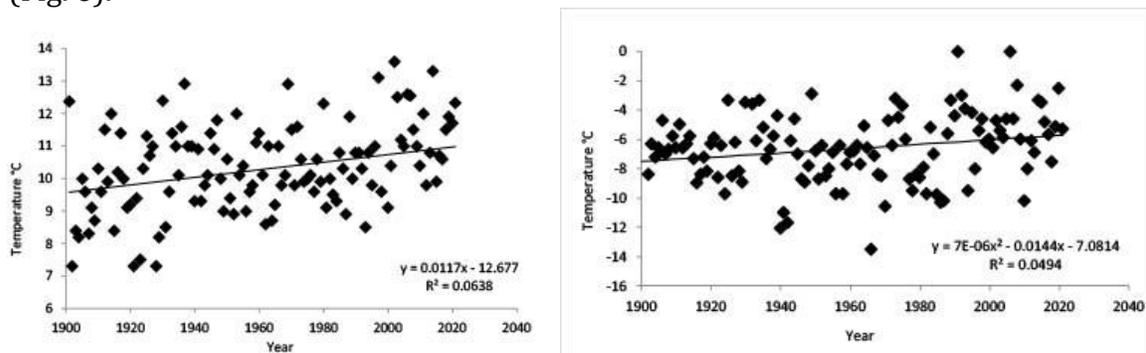


Figure 5. Mean annual regional air temperatures recorded at Storlien/Storvallen meteorological station, 1901-2021. Left. June-August. Right. December-February. Source: Swedish Meteorological and Hydrological Institute

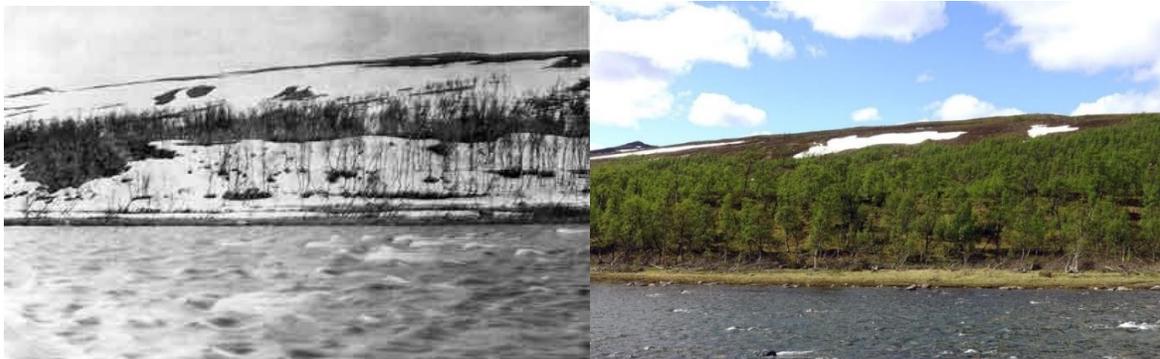


Figure 6. Birch leafing and snow phenology. Left. By the early 20th century, just prior to the onset of the modern warming phase, snow cover persisted well into the mid of June, accompanied with relatively late birch leafing Right. Annual monitoring since 1977, has provided a view of much earlier birch leafing and snow melt, each year virtually the same appearance as the one depicted here. Mt. Lillulvåfjället, east-facing slope, from 740 m a.s.l. Left. Photo: 1914-06-11 (Harry Smith). Right. Photo: 2019-06-11

METHODS

Since the early 1970s, various geobotanical case studies have been carried out in the southern Swedish Scandes, with particular focus on the present and past landscape of the Handölan River Valley and adjacent mountains. The main focus has been on treelines and treeline performance in relation to climate change and variability and its interactions with historical land use. The main intention with this paper is to bring about a review and synthesis of these studies as a legacy to future students of geocological research in these mountains.

The narrative starts with the long-term (Holocene) perspective and proceeds with an account of modern time dynamics, i.e. the last 100 years, in the form of reviewed and updated case studies.

The Holocene arboreal and deglaciation histories in the mountain region are mainly based on megafossils, which is the approach that can most accurately decipher the broad course of change in space and time (Kullman 2017a, 2018; Paus & Haugland 2017). Novel and promising

paleoenvironmental approaches, e.g. analyses of ancient DNA (Parducci et al. 2012; Parducci 2019; Nota et al. 2022) may provide a fundamental paradigm shift in vegetation history, but are too imprecise and beset with interpretational uncertainties and still in their infancy (cf. Birks et al. 2012; Alsos et al. 2020; Paus 2021). Notwithstanding, high-elevation arboreal history, based on megafossils, provides the most accurate minimum dates of true presence of trees and deglaciation. These measures are more precise and substantially earlier than inferred by some immature physical methods, e.g. terrestrial cosmogenic nuclide (TCN) dating (e.g. Johnsen 2010).

TREELINE SOIL TEMPERATURES: A 21 YEAR TIME SERIES RECORD

In general, treeline position and structure are renowned as closely related to climate (Tranquillini 1979; Holtmeier 2009; Körner 2021). Over the years, much effort has been devoted to define a general mechanism and control behind the treeline phenomenon. In that respect, the importance of soil temperature has been much in focus (Karlsson & Nordell 1999; Körner & Paulsen 2004; Körner 2012; Müller et al. 2016). These studies have suggested a critical minimum limit of 6.4-7.1 °C for the growing season.

The issue, focused above, was addressed by a 21year record of summer and winter soil temperatures at site in the upper birch treeline ecotone of the study area (Mt. Storsnasen). The concerned birch stand is located at 850 m a.s.l., which is 45 m above the treeline position by the early 20th century (Kullman & Öberg 2009). Details of the study and its results are provided by Kullman (2021e). Summer and winter views and recorded temperatures of the studied birch stands are given by Figures 7 & 8, respectively. The obtained results indicate a critical value of 7.1 ± 0.7 °C for the growing season soil temperature and support the general validity of data from the literature, cited above.

Present day evolution to tree stature coincides with the modern warming phase, which stimulated rapid height growth of these specimens. The concerned birches prevailed as low-growing shrubs, as inferred from insignificant radial growth prior to the onset of 20th century climate warming (Fig. 9). A progressive growth response was particularly strong up to the late 1930s, whereafter more stationary conditions have prevailed.





Figure 7. Summer and winter views of the surveyed birches, comparing the situation 2010 and 2020. Some proliferation of ramets and height increment may be discerned. In addition new specimens have emerged in in the center of the formation. Photos: Upper left. 2010-07-29. Upper right. 2020-07-15. Lower left 2010-02-03. Lower right. 2020-03-07. Source: Kullman 2021d

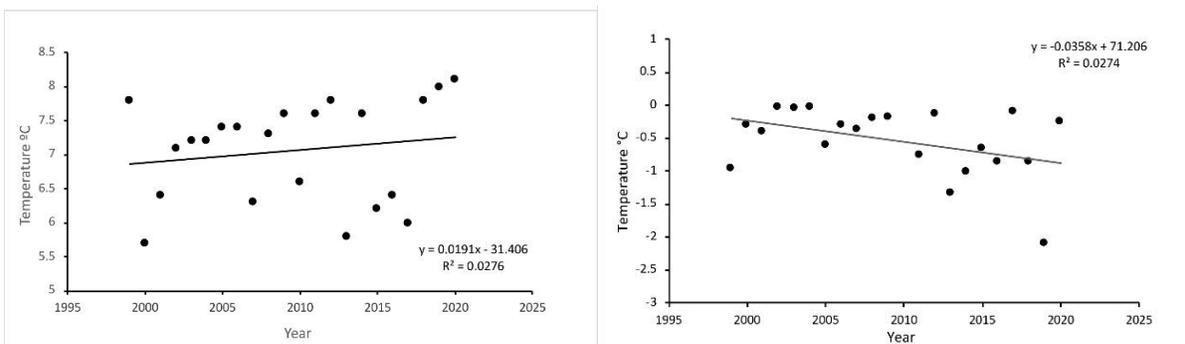


Figure 8. A. Mean annual regional air temperatures, June - August (left) and December-February (right), recorded 1999-2020 at Storlien/Storvallen meteorological station. Source: Kullman (2021e)

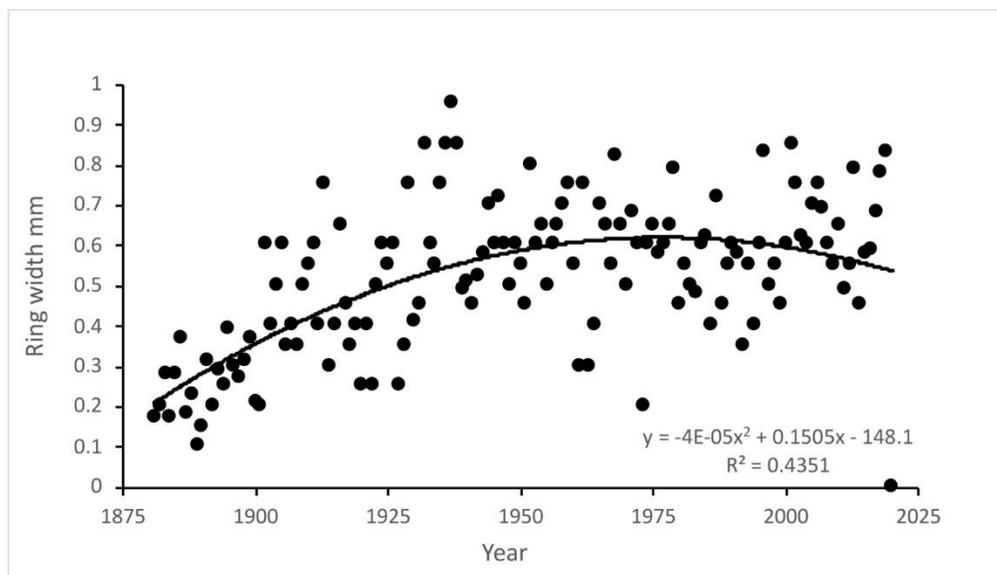


Figure 9. Annual radial growth (1880-2020), as means of four birch trees, with soil temperatures surveyed since 1999. Source: Kullman (2021e).

HOLOCENE ARBOREAL HISTORY FROM DEGLACIATION TO THE LATE 19TH CENTURY- EVIDENCE FROM MELTING GLACIERS AND EMERGING MEGAFOSSILS

The study area contains the southernmost glaciers of the Swedish Scandes. Like many glaciers world-wide (Luckman 1998; Schlüchter & Jörin 2004; Nesje 2009; Koch et al. 2014, Solomina et al. 2015; Zemp 2015), they have receded during the relatively warm post-Little Ice Age period of the past 100 years or so (Öberg & Kullman 2011), as depicted by Figures 10-11. The onset of this process followed gradually on the nadir of the Little Ice Age (late 17th and early 18th century) and was accentuated during the 1920s. Recession accelerated with a peak by the relatively warm 1930s (Mannerfedt 1945; Lundqvist 1969) and has thereafter proceeded smoothly, with transient halts and minor reversals up to the present day (Lundqvist 1969; Holmlund 2012).

Modern glacier recession in the southern Scandes is paralleled by permafrost disintegration (Smith 1957; Lundqvist 1969; Nihlén; 2003; Hofgaard & Myklebost 2015) (Fig. 12).

At their recently ice-freed forefields, glaciers and large semi-permanent snow patches are displaying megafossils of different tree species. These new discoveries, along the entire Swedish Scandes, make clear that the glaciers have been preceded by tree stands 11 000-5000 cal. a BP or so, following the regional deglaciation and prevailing in a climate more favorable than at present. Early Holocene “hidden” tree enclaves were located 600-400 altitudinal meters above their respective present-day treelines. These high treelines imply, adjusted for land uplift, that summer temperatures during the very first part of the Holocene may have been about 3.0-2.5 °C higher than at the present day (Öberg & Kullman 2011; Kullman & Öberg 2015, 2020). This pattern appears common to the entire Swedish Scandes (Kullman & Öberg 2015; Kullman 2017b). Macrofossils (needles) provide a virtually similar view in the Dovre Mountains of central Norway (Paus et al. 2011).

From a palaeoclimatic point of view, the recovered high-elevation megafossils sustain the view that the postglacial thermal maximum in northern Europe was in the earliest part of the Holocene, in ultimate accordance with orbital climate forcing (cf. Nesje 2009; Kullman 2008a, 2013; Luoto et al. 2014; Väiliranta et al. 2015; Paus & Haugland 2017; Mangerud & Svendsen 2018; Helmens et al. 2018).

Following the early Holocene thermal maximum, oscillatory climate cooling and treeline retreat have proceeded in concert up to the late 19th century (Kullman 2013). The vegetation of the present-day low-alpine region is inferred as the rearguard of the demised arboreal vegetation, as evidenced by megafossils, podzolic soils and relict plant communities with forest affinities (Kullman & Öberg 2018; Odland 2021).

Below is an account of megafossil tree remains, recently released from the grip of glacier ice and perennial snow in the study area (Figs. 13-17). Radiocarbon dates of megafossils are given as calibrated years before present (cal. a BP), with present = AD 1950. For simplicity, so-called intercept ages are used to represent each sample.



Figure 10. The *Storsylglacier*, like other glaciers in the study area, has retreated substantially during the past 100 years. Left. Photo: Fredrik Enquist, 1908. Right. During the past 100 years, the area has diminished by > 50 %. 2021-09-15.

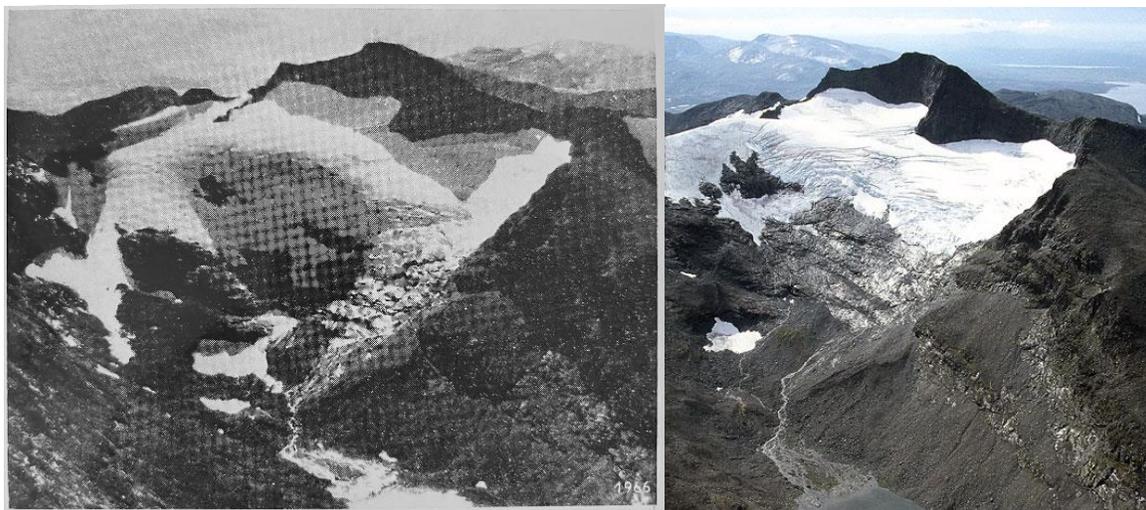


Figure 11. Left. Aerial view of the *Storsylglacier* 1966 (Lundqvist 1969). Right. Virtually the same prospect 39 years later, showing modest recession at the lower front. Photo: 2005-08-15.



Figure 12. During the Little Ice Age, permafrost formed in low alpine peatlands, in this case a low *palsa*. Nowadays, in response to climate warming, these structures are currently thawed and are obliterated. Mt. Östra Helagsskafet, 900 m a.s.l. Photo: Harry Smith, 1910-08-24.



Figure 13. Left. Megafossil birch trunk exposed at the fringe of the meltwater pool below the Storsylglacier, 1275 m a.s.l. Reasonably, the stem has been down washed from a growing site higher upslope. After the relief from the grip of ice, the stem has been preserved beneath a moss-cover. Radiocarbon-dating yielded 7170 cal. a BP. Photo: 2008-08-24. Right. Pine log at the lower forefield of the Storsylglacier, 1195 m a.s.l., about 400 m higher than the present treeline. The trunk was dated 10 425 cal. a BP. Photo: 1997-07-16

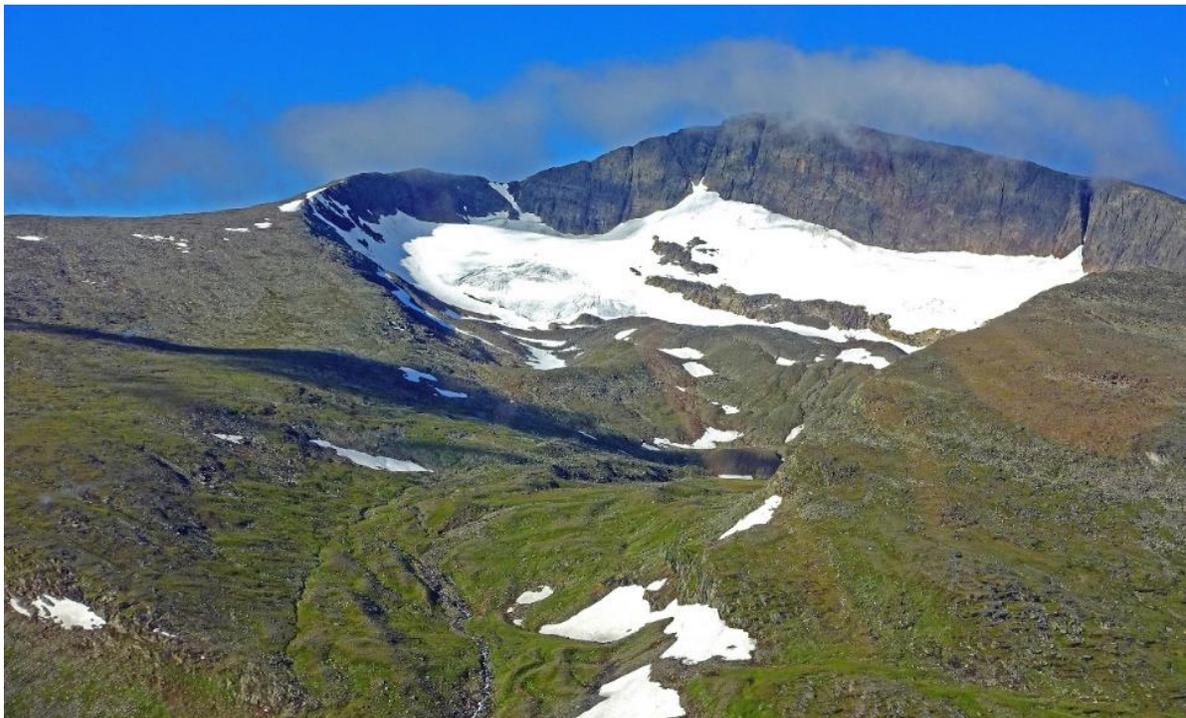


Figure 14. The Helagsglacier. The area has become about 40 % smaller during the past 100 years. Megafossils are exposed at the lower margin and are dislocated downslope by gravitational forces (Fig. 15). Photo: 2015-08-13.



Figure 15. Left. The lower fringe of a perennial snow field below the Helagsglacier, 1150 m a.s.l. Right. Wood remnants of pine (*Pinus sylvestris*) have been exposed here and dated 13 145 cal. a BP. Analogous late-glacial recoveries are reported from parts of the Scandes, further north. Photo: 2008-07-04

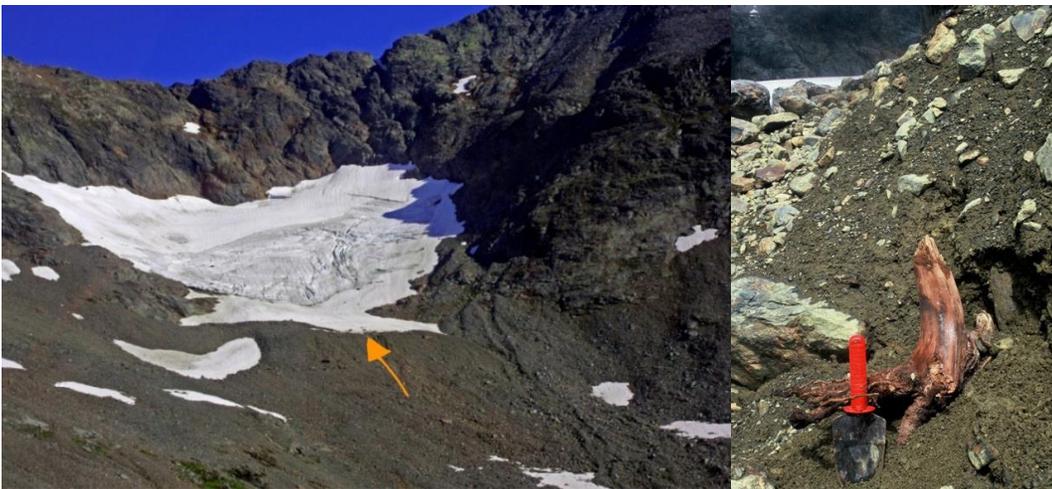


Figure 16. Left. The Ekorr glacier in the Sylarna Massif has shrunk and retreated substantially since the early 20th century. Right. Basal part of a birch, dated 8710 cal. a BP. The finding, 1345 m a.s.l., was made in an eroding frontal moraine, damming a small meltwater pool at the lower margin of the glacier. The location is indicated by an arrow. Photo: 2003-07-12. Source: Kullman (2004)

Outside and below the ice-emptied glacier cirques and high above present-day treelines, megafossils are regularly found in various depositories, such as peat and lake sediments (Figs. 17 & 18). These witnesses provide new biogeographic and glacio-geological data. They add to the comprehension of the structure and composition of the early postglacial living mountain landscape and its continuous transformation into modern time design. This present study area is unique in its wealth of such information, based on various proxy sources (Smith 1920; Kilander 1955; Lundqvist 1969; Kullman & Kjällgren 2000, 2006; Kullman 1983 a,b; 2002 a,b, 2013; Hammarlund et al. 2004; Bergman et al. 2005).



Figure 17. Outside the glacier sites, this is the most common type of megafossil (pine, birch and spruce), showing higher-than-present Holocene treelines. This pine log dated 7000 cal. a BP and is preserved in peat about 200 m above the modern pine treeline, within a landscape typified in Figure 3. Mt. Miesehketjahke, 900 m a.s.l. Photo: 2009-08-08



Figure 18. Left. By the Late-Glacial/Holocene transition, trees grew on early deglaciated nunataks. Mt. Lillsnasen. Photo: 2007-10-02. Right. Megafossil pine remnants were retrieved from the small pond in the upper distant part of the image. Radiocarbon-dating yielded 11 215 cal. a BP. Conventionally, the mountains have been assumed ice-covered at this time. Photo: 1999-07-04

For example, earlier high-mountain deglaciation and tree emergence are some of the new features of the late-glacial landscape, that stand out from the megafossil approach. Earlier common perception of high-mountain deglaciation, just shortly prior to 10 000 cal. a BP (e.g. Lambeck et al. 2010; Bergman et al. 2005; Johnsen 2010; Stroeven et al. 2016) are questioned in that perspective. All available dating results of megafossils (pine and birch) from the study region are displayed in Figures 19 & 20.

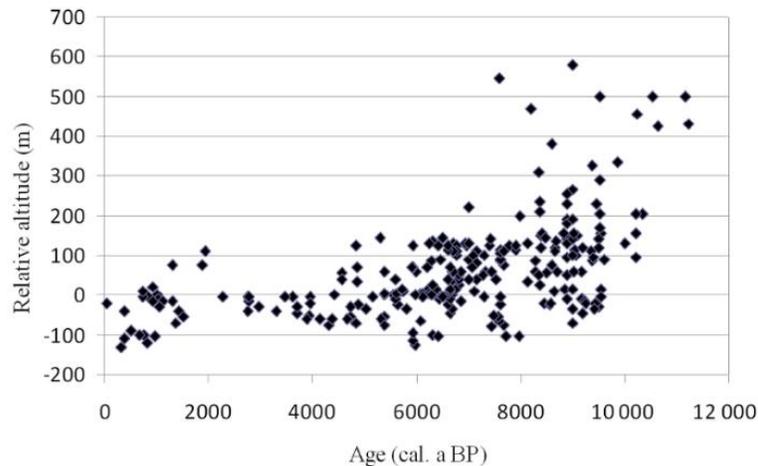


Figure 19. Composite of all radiocarbon dates (old and new) of pine, relative to the altitude of the present pine tree line (2010). Source: Kullman 2013.

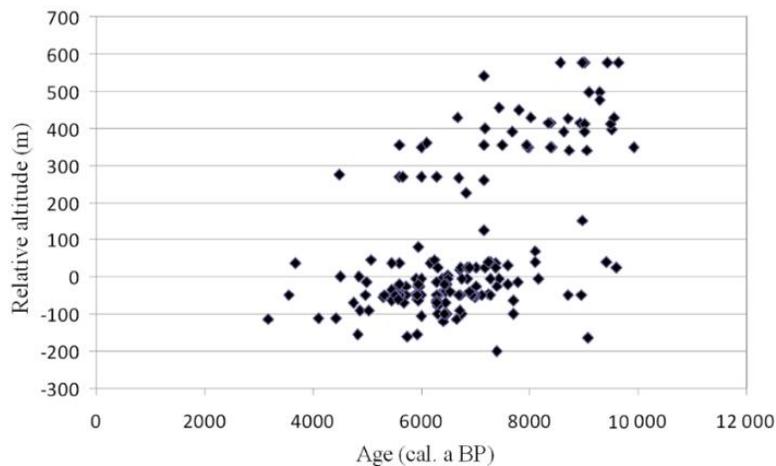


Figure 20. Composite of all radiocarbon dates (old and new) of mountain birch, relative to the altitude of the present birch tree line (2010). Source: Kullman (2013).

Contrary to prior common pollen-based belief (e.g. Huntley & Birks 1983; Giesecke & Bennett 2004; Seppä et al. 2009), Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) grew on early nunataks both in Sweden and Norway during the Late Glacial and early Holocene (Kullman 1996 b; 2002b, 2008 a, 2017a,b, 2022 a,b; Paus 2021; Paus et al. 2011). The highest recovery of spruce was close to the summit of Mt. Storsnasen in the study area, 1405 m a.s.l. (Fig. 21).



Figure 21. During the early Holocene (9300 cal. a BP) spruce grew at an extremely high and exposed site 60 m (arrow) below the summit of Mt. Storsnasen, 1463 m a.s.l. (Kullman 2022b). This finding further nourishes the notion of early Holocene peak temperature as well as early presence of Norway spruce (*Picea abies*) in the Scandes. Photo: 2012-06-15. Source: Kullman (2022 b).

These recently obtained results raise questions as to spruce tree positions during the peak of the Weichselian glacial phase and its subsequent performance and spread over Scandinavia (Segerström & von Stedingk 2003; Alsos et al. 2020; Parducci et al. 2012; Nota et al. 2022). In particular, the earlier view of gradual spruce immigration to Scandinavia from the east (eg. Giesecke & Bennett 2004) is revised in this new light (e.g. Kullman 2000, 2022b).

Another new feature is that Siberian larch (*Larix sibirica*), occurred at high elevations along the entire Scandes (the study area included) during some early Holocene millennia (Kullman 1998d, 2018), is shown by Figure 22. This is inferred also from pollen data in Norwegian mountains about 10 200 cal. a BP (Paus 2010).



Figure 22. Left. Cones of *Larix sibirica* and *Picea abies* recovered and slightly uplifted, close to the surface of an open mud area close to the present-day treeline of mountain birch. Right. Radiocarbon dating yielded 9635 cal. a BP (*Larix*, small cones) and 6090 cal. a BP (*Picea*, large cone), respectively. Mt. Sylarna, 910 m a.s.l. Photos: 1996-08-06. Source: Kullman (1998c).

THERMOPILOUS TREE SPECIES DURING THE WARM EARLY HOLOCENE

Aside of exceptionally high treelines of boreal tree species during the early Holocene, the megafossil record adds the presence of some relatively more warmth demanding (nemoral) trees. These recoveries were made at quite high elevations where mountain birch prevails at the present day. This circumstance further strengthens the view of an early postglacial thermal and biodiversity optimum and a living landscape quite different from present-day depauperized state (Smith 1920; Helmens, Katrantsiotis, Salonen et al. 2018).

This situation is expressed by macro- and megafossil remnants of tree species currently confined to more southerly regions and lower elevations of Scandinavia (Fig. 23 & 24). These species are oak (*Quercus robur*), elm (*Ulmus glabra*), lime (*Corylus avellana*) and black alder (*Alnus glutinosa*). More detailed accounts of these findings, not visible in traditional pollen records, are given by Kullman (1998 b, d, 2015b, 2020a, 2021e).



Figure 23. Erosion scar in a sloping fen, with predominant *Carex lasiocarpa*, in the lower subalpine birch forest belt, where macrofossil leaves of thermophilic tree species were unearthed. Mt. Getryggen, 740 m a.s.l. Photo: 2022-09-20. Source: Kullman (1998b)



Figure 24. Macroscopic remnants of thermophilic tree species, recovered from an eroded peat deposit at the site visualized in Fig. 23. Left. From left to right; *Ulmus glabra* (9445 cal. a BP), *Quercus robur* (8965 cal. a BP), *Alnus glutinosa* (9260 cal. a BP). Right. Nuts of *Corylus avellana* dated 9250 cal. a BP. Source: Kullman (1998b)

A MEDIAEVAL HIGH TREELINE ANOMALY AND RETRACTION DURING THE SUBSEQUENT LITTLE ICE AGE

A period relatively high temperatures prevailed worldwide for some centuries after about 1000 cal. a BP, the so-called Mediaeval Climate Anomaly (MCA), which interrupted the long-term (Neoglacial) Holocene cooling, which has lasted for about 5000 years. The exact geographical

extent and magnitude of temperature deviation relative to the present day is discussed (cf. Lamb 1982; Broecker 2001; Hegerl et al. 2007; Ljungqvist et al. 2012; Kullman 2015a; Helama et al. 2020; Vinós 2022).

In the study area, megafossils representing this period are legio at somewhat higher elevations than the modern (early 21st century) pine treeline (Fig. 25). Between the late 13th and early 15th century, the pine treeline was located 110-115 m or more above the present level in the study area and elsewhere in the North (Karlén 1976; Hiller et al. 2001; Shiyatov 2003; Kremenetski et al. 2004; Mazepa 2005; Esper & Frank 2009; Kullman 2013, 2015a; Linderholm et al. 2014; Helama et al. 2020). This circumstance indicates warmer than present conditions by at least 0.7 °C during the summers. In the context of the common discourse concerning anthropogenic future climate warming, the existence of this episode has become politically inconvenient as it represents natural warmer-than-present conditions, obviously for natural reasons (cf. Esper & Frank 2009). Given the periodic climate variations during the Holocene, it has been discussed where the modern warming (post-Little Ice Age), mainly represent a recovery, analogous to the Mediaeval Climate Anomaly (cf. Denton & Karlén 1973; Vinos 2022).



Figure 25. Remants of pines, recovered above the present-day treeline They established during the Mediaeval Climate Anomaly and demised during the subsequent Little Ice Age. Mt. Täljstensvalen. Left. 735 m a.s.l. Photo: 2022-07-22. Source: Kullman 2017b. Right. 770 m a.s.l. Photo: 2011-10-27. Source: Kullman (2013)

Following on the Mediaeval Climate Anomaly, harsher centuries ensued, the so-called Little Ice Age. Its duration was between the 15th and late 19th century. The mean temperature in the Northern Hemisphere dipped by 0.5-0.7 °C for long periods of time. Obviously, this was the coldest period of similar length during the Holocene, although interrupted by more amenable conditions for shorter periods (Lamb 1982; Grove 1988; Matthews & Briffa 2005; MacDonald et al. 2008; Büntgen & Hellman 2014, Vinós 2022).

Different lines of evidence sustain that perceivable glacier and permafrost expansion as well as treeline depression took place during this epoch, as reviewed by Kullman (2015). Treeline retraction and upper forest dieback were conspicuous processes in the study area, as witnessed by subfossil tree logs and snags (mostly pine) above the current treeline (Kullman 1987, 2005a,b, 2015a; Kullman & Öberg 2021). Eyewitness reports from the Handölan Valley account for continuous thinning of marginal pine stands, being replaced by mountain birch (Nilsson &

Norling 1895; Sernander 1899). Figures 26-27 visualize arboreal legacies of this dire and severe climatic phase of the Neoglacial period.



Figure 26. Megafossil pine remnant, which dated 1050 cal. a BP, representing “higher than-present” tree line of pine during the Mediaeval Climate Anomaly and subsequent 75 altitudinal meter depression during the Little Ice Age. Mt. Norder Tväråklumpen, 780 m a.s.l. Source: Kullman (2015a).

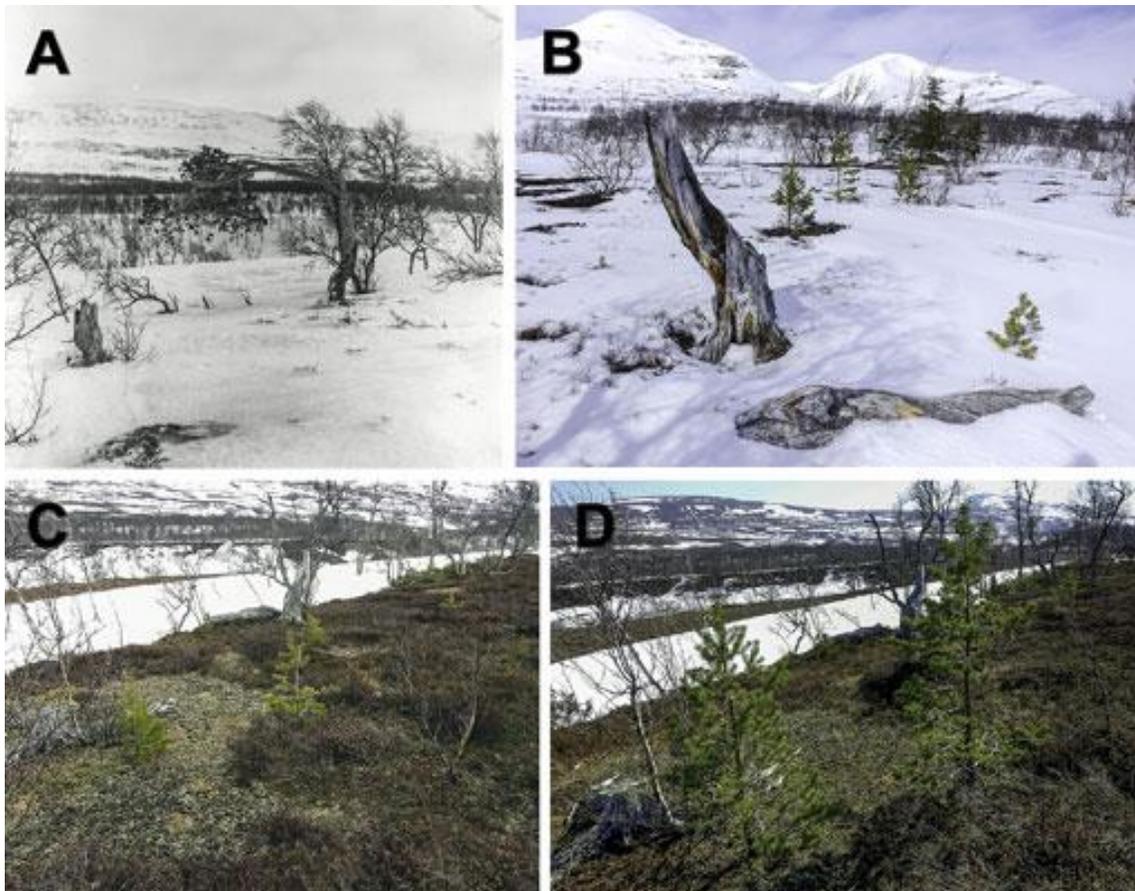


Figure 27. A. This moribund pine tree germinated in the mid-17th century and was the northernmost pine tree in the Handölan Valley (705 m a.s.l.) by the mid-1970s. The tree was the last survivor of a local stand that was gradually extirpated during the Little Ice Age (Kullman 1987). B. It was finally broken in a winter storm 2005/2006. C. Just before its demise, it gave birth to a cohort of 12 saplings in a near circumference. D. These young pines had reached height of 2.0-2.2 in 2020. Photos: A. 1977-02-03. B. 2016-02-29. C. 2013-05-08. D 2019-04-28.

A RECENT COOLER PHASE – PERMAFROST AGGRAVATION AND TREELINE RECESSION

Recent and proposed future climate warming are high on the public and scientific agenda (IPCC 2013). In that perspective, it is easy to forget that nested within the general warming trend of the past 100 years, there was a causally unexplained cooling period of some decades, following upon the warm 1930s. This cooler interval (winters in particular) prevailed roughly between 1940 and 1990 (Figs. 5 & 28) and has been particularly highlighted and discussed by some researchers (Eriksson 1987, 1988; Eriksson & Alexandersson 1990; Bengtsson et al. 2004).

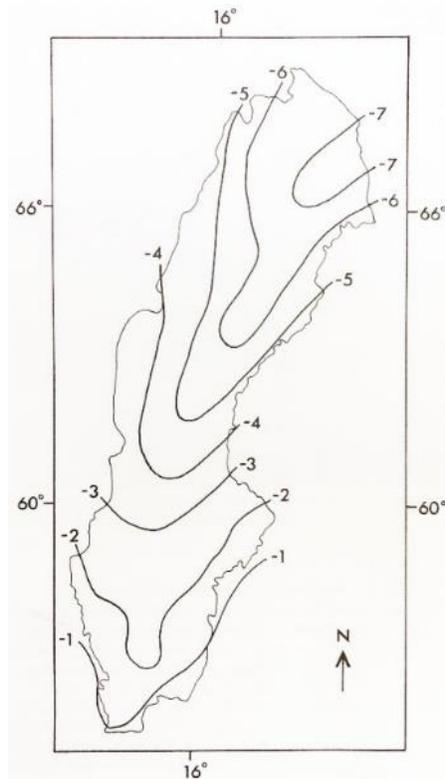


Figure 28. Deviation in Sweden (°C) in winter temperature (December-February) between the warm period 1931-1940 and the colder one (1978-1987). Source: Eriksson 1988.

Geocological consequences, following on cooler conditions after the 1930s (Fig. 5), were clearly perceivable on the arboreal landscape in the North by the early 1970s and culminated in the late 1980s. Transient spread of permafrost, aggravated seasonal ground frost and activation of various periglacial manifestations were distinct manifestations of lower temperatures in the study area (Kullman 1989a,b, 1991a) (Fig. 29). These processes were ubiquitous all over northern Fennoscandia and other subarctic and subalpine regions (Schunke 1979; Karte 1983; Jalkanen 1985; Grove 1988, 2004; Grove 1988, 2004; Kullman 1989a,b,c, 1991a,b; Ritari 1990; Tikkanen & Raitio 1990; Josefsson 1990; Seppälä 1998). In addition, some transient glacier advance took place in the study area and in Norwegian Mountains (Lundqvist 1969; Nesje 2009).



Figure 29. New permafrost formed in peat hummocks 1986/87 within the lower birch forest belt. After the early 1990s, thawing has occurred by late June or early July. Mt. Storsnasen, 680 m a.s.l. Photo: 1987-09-28.

A conspicuous consequence in northern Fennoscandia of the cold 1980s, was widespread needle loss, crown thinning and mortality of juvenile and mature conifers close to the treeline (Kullman & Högberg 1989; Kullman 1989a,b,c, 1990, 1991 a,b, 1996a; Tuovinen et al. 2005). This process is exemplified by Figures 30-32. Analogous responses were assessed for mountain birch within its treeline ecotone (Kullman1989b). In the case of *Picea abies*, forest decline during this episode affected the entire landscape appearance.



Figure 30. Upper spruce forest stands, mixed with mountain birch, on a slope close to the mouth of the Handölan Valley, suffered 70-75 % needle loss during the extremely cold and snow-poor early winter 1986/87, which lended the landscape a greyish hue. W-facing flank of Mt. Täljstensvalen. Photo: 1987-08-14.



Figure 31. Left. Treeline spruce which suffered extensive needle loss during the winter 1986/87. Notably, a skirt of branches close to the ground were virtually unaffected, due to snow protection during most of the winter. Photo: 1988-04-14. Right. Over the past 30 years, the spruce has regained most of its lost foliage. Photo: 2016-05-26 Täljstensvalen, 700 m a.s.l



Figure 32. High-elevation pine stand with extensive needle loss and some mortality of young and old individuals. In fact, permafrost formed on these peatlands during the summers of 1987 and 1988. A majority of depicted trees derive from the post-1930, period. It was inferred that vigor loss related to frost desiccation and/or fine root mortality. Henning (1895) surveyed virtually the same site by the end of the Little Ice Age, and then observed dying old pines and saplings in bad condition. He concluded that the reason for this dire aspect was the presence of frozen soil still in mid-August, just like the situation in 1987 and 1988. Mt. Storsnasen, 575 m a.s.l. Photo: 1987-06-25. Source: Kullman & Högberg (1989).

PREDIKSTOLEN - A GEOBOTANICAL LINK BETWEEN PAST AND PRESENT

Mt. Predikstolen is the southernmost outlier of the Helagsfjället-massif. The steep S-SW-facing slopes provide favorable local thermic conditions, wind protection and a steady meltwater

supply from higher elevations (Fig. 33). These are the prerequisites for high treelines and a rich present-day flora, with affinities to past times with a warmer climate (Smith 1951). Examples of residual warmth-demanding plant species are, *Ajuga pyramidalis*, *Cotoneaster scandinavicus*, *Anthyllis vulneraria* ssp. *lapponica*, *Saxifraga adscendens* and *Anthriscus sylvestris* (Fig. 34). Except for extensive reindeer grazing, this remote area is relatively little affected by human activities in the past.



Figure 33. The characteristic SE-facing projection (1400 m a.s.l.) of Mt. Predikstolen (1682 m a.s.l. Photo: 2015-08-13.



Figure 34. Thermophilic plant species growing in the south-facing slope of Mt. Predikstolen. Left. *Ajuga pyramidalis*, 1050 m a.s.l. Mid. *Cotoneaster scandinavicus*, 1030 m a.s.l. Right. *Anthyllis vulneraria* ssp. *lapponica*, 1030 m a.s.l. Photo: 2009-07-04.

By the early 20th century, the botanist Harry Smith surveyed birch treeline positions in the southwest-facing slope of this mountain (Smith 1920) and recorded it at 885 m a.s.l. He resurveyed this site in 1950 and found the treeline was now located at 990 m a.s.l., i.e. a rise by 105 m. At the same period of time, he noted creeping shrubs growing at 1000 m a.s.l., i.e. potential for further upslope advancement of treeline by accelerated height increment of preestablished individuals. By the mid-1970s, the treeline had risen to 1035 m a.s.l. (Kullman 1979). Thereafter, the treeline advanced to 1060 m a.s.l., ie. a total progressive treeline displacement by 175 altitudinal meters over the past 100 years. This process is displayed by Figure 35. The obtained figure matches maximum treeline upshifts along the entire Swedish Scandes (Kullman 2021a) and adds to the notion that the driving forces are extra-local, most likely regional climate warming. Aside of treeline advance, some “forest” establishment has taken place in the barren lower slopes of the early 20th century.



Figure 35. After the mid-1970s, the birch treeline has taken a further step to a higher elevation, 1060 m a.s.l, which means a total upshift by 175 m over the past 100 years. Photo: 2015-08-13.

In addition to treeline rise, the low alpine plant cover in the Predikstolen area and in the region as a whole, has changed perceivably in concert with climate warming during the past 100 years. This has been conceived by repeated line transect analyses of the proportions of distinct plant communities. These studies were initiated by Smith 1920, repeated by the same author (Smith 1957) and continued by Kullman (2004).

It was inferred from these analyses that a fundamental ecological aspect of the new and warmer climate and its impact on the plant cover, is mediated by earlier and more complete melting of the snow cover, This leads to some drying out of the lower alpine slopes during the late summer. Most conspicuous, within the entire study area, by tradition are the dwindling snow bed communities, where characteristic ferns (*Athyrium distentifolium*) and small highly specialised herbs and ferns, e.g. *Cassiope hypnoides*, *Sibbaldia procumbens*, *Gnaphalium supinum* and *Athyrium distentifolium* are giving way to dense and extensive alpine grass communities (*Avenella flexuosa* and *Deschampsia cespitosa*) (Fig. 36). Moss-rich dwarf-shrub heaths with *Vaccinium myrtillus*, *Betula nana* and *Empetrum hermaphroditum* have gained increasing importance at the expense of lichen-rich communities. Drying-out fens are converted to meadows with tall shrubs (*Salix* and *Betula*). Moreover, the relative proportions of open water and naked rocks have diminished.



Figure 36. Expanding grass-heath (*Deschampsia cespitosa*) downslope of a late-melting snow patch, that has dwindled during past decades in response to ceasing meltwater during the late summer. Mt. Getryggen 1045 m a.s.l. Photo: 2017-09-14. Source: Kullman (2008).

A particularly conspicuous happening, seemingly related to a warmer climate in the flora of Mt. Predikstolen, is the establishment of a sapling of the thermophilic *Quercus robur*, only slightly

below the birch treeline, 1020 m a.s.l. (Fig. 37). This is quite remarkable, since *Quercus* is, “by tradition”, not a member of the northern boreal flora in Sweden.



Figure 37. A sapling of *Quercus robur* was quite recently recovered in the south-facing slope of Predikstolen, 1020 m a.s.l. Photo: 2008-07-04. Source: Kullman (2008b)

Smith (1920, 1951, 1957) did not mention presence of coniferous tree species on the slopes of this mountain. Nevertheless, today a 2.5 m high spruce tree grows close to the mountain side rock-face in the south-facing slope, 1075 m a.s.l., i.e. slightly higher than the treeline of mountain birch (Fig. 38). Tree-ring counting shows that it existed here by the end of the 19th century, presumably as a low shrub. This specimen manifests treeline rise by about 200 m over

the past 100 years or so. In addition, scattered saplings of pine and spruce have recently appeared at and above the birch treeline, possibly spread from the west, i.e. Norway (Fig. 39).



**Figure 38. A spruce tree, tightly pressed to the steep rock-face of Mt. Predikstolen, 1075 m a.s.l.
Photo: 2008-07-04.**



**Figure 39 Left. Pine sapling, 1080 m a.s.l. Right. Spruce sapling, 1065 m a.s.l. Mt. Predikstolen.
Photos: 2008-07-04.**

Overall, these changes outlined above have given the landscape a richer, greener and a lusher appearance (Fig. 40) (Kullman 2010b).

Possibly, further fundamental restructuring of the alpine plant cover may lie ahead, given that the climatic amelioration of the past 100 years proceeds unabated. Reasonable analogues for such a purely hypothetical prospect may be found in the Mediaeval and early Holocene flora and vegetation (cf. Kullman & Öberg 2020).



Figure 40. Since the early 20th century, repeated analyses of the relative proportions of different plant communities, have been carried out to the southwest slope of Mt. Predikstolen. Overall, the landscape has become lusher and greener, 905 m a.s.l. The cover of moss-rich dwarf-shrub heaths has increased, fens have dried out and snow bed communities have dwindled. Mt. Predikstolen, 905 m a.s.l. Photo: 2008-07-04. Source: Kullman (2007a,b, 2010 b).

RECENT PINE ADVANCE TOWARDS THE HEAD OF HANDÖLAN VALLEY AND BIRCH FOREST EVOLUTION

By the early 20th century, in consequence of the long-term (Neoglacial) climate cooling, the pine treeline had retreated to its lowest position ever. In the study area, on both sides of the river, this position was 705 m a.s.l. and 6.5 km to the south of the village Handöl (Sernander 1901; Andersson 1903). By the late 19th century, the last survivors and the trailing edge of pine trees prevailed at that position (Fig. 27), upheld by old-established moribund and dying trees (Nilsson & Norling 1895; Sernander 1899). Still by the late 1970s, these old-growth pine trees were the treeline in the valley (Kullman 1981a, 1986b). Concurrent with the long-term pine demise, a denser birch forest cover has emerged.

A distinct pine reproduction surge, initiated during the 1930-1940s, and particularly after 2010, has given rise to the establishment of sparsely spaced pine trees and frequent saplings at higher elevations further south and at higher elevations in the Handölan Valley. Accordingly, the treeline has penetrated deeply into the birch forest and has advanced c. 12 km southwards and to a 95 m higher elevation (Kullman 2017b, 2021b) (Fig. 41&42). A possible pending continuation of that process within the treeline ecotone is supported by a distinct pulse of

proliferous reproduction after about 1990 and particularly during the past 10-15 years (Kullman 2014b, 2017b, 2021b; Kullman & Öberg 2021), as evidenced by Figures 43-47. Winter injuries and mortality (frost desiccation) have been relatively insignificant, compared to the 1970s and 1980, when mortality/injury and recruitment rates were high and low, respectively (Kullman 1993). Thereafter, winter minimum soil temperatures have been relatively high (near 0°C) within in the entire treeline ecotone of the study area (Kullman 2007c, 2014b, 2021c,d). In addition, this progressive course of change is contingent on a distinct rise of treeline pine seed viability, most pronounced since the late 1990s (Fig. 48). Conspicuously, recruitment of mountain birch has not responded analogously to the pine. This difference may relate to evergreen pine's ability to take advantage of earlier snow melt, compared to deciduous mountain birch (cf. Oksanen & Virtanen 1995).

Possibly, we are currently witnessing a fundamental ecosystem shift in the mountain regions, as pine is advancing on all fronts (Kullman 2019; Kullman & Öberg 2021), regaining some of its more dominant role in the early Holocene when temperature apparently reached an all-time-high (Kullman 2013; Paus & Haugland 2017). Accordingly, modern climate and biotic evolution are well within the range of natural dynamics, let be on the warmer fringe (Ljungqvist et al. 2012),

In concert with the outlined pine progression, and obviously a prerequisite of that process, is a partial regression of the extant birch forest cover and drying out of mires and alpine/subalpine soils in general. In addition, reindeer grazing has extirpated lichen mats over large parts of the valley floor birch forest (Fig. 49). This course of change, in combination with a secular trend of enhanced late-summer drought, in response to earlier snow melt and diminishing broad-scale supply of meltwater (Ahlmann 1953; Smith 1957), may have been beneficial to pine growth.

In addition, some subalpine birch forest thinning and decline in the southernmost Swedish Scandes. This course of centennial change has enabled sparse pine tree stands to "leap-frog" over the birch forest belt and the pine treeline, to ascend to its highest position over the past 7000 years of the Holocene (Kullman 2017b, 2021a). This circumstance adds to the anomalous character of the climate of the 100 years, as inferred also from glacier history (Bakke et al. 2008; Koch et al. 2014). Accordingly, it has been speculated that the mountain birch belt will become transformed into a subalpine pine belt, given that the current relatively warm phase prevails (Holtmeier 2005; Kullman 2014b, 2015c, 2017b).

In the study area, with its more oceanic and snow-persistent climate, the transformation has yet not proceeded that far. However, drying out soils and birch stand recession are common features in water recharge segments of the local small-scale topography (Fig. 50), where pine currently establishes scattered saplings (Fig. 51). For the same basic reason, birch is now able to fill and grow in depressions, where excess of snow previously precluded tree growth (Fig. 52). Conspicuously, birch is currently invading directly into preexisting snow-bed vegetation (Fig. 53). Hereabouts, birch forest stands are growing increasingly dense.

In other words, the initial phase of a fundamental reorganization of the subalpine region may lay ahead, with birch migrating into the svaes and leaving snow-poor convexities open to pine establishment (Kullman 2019).

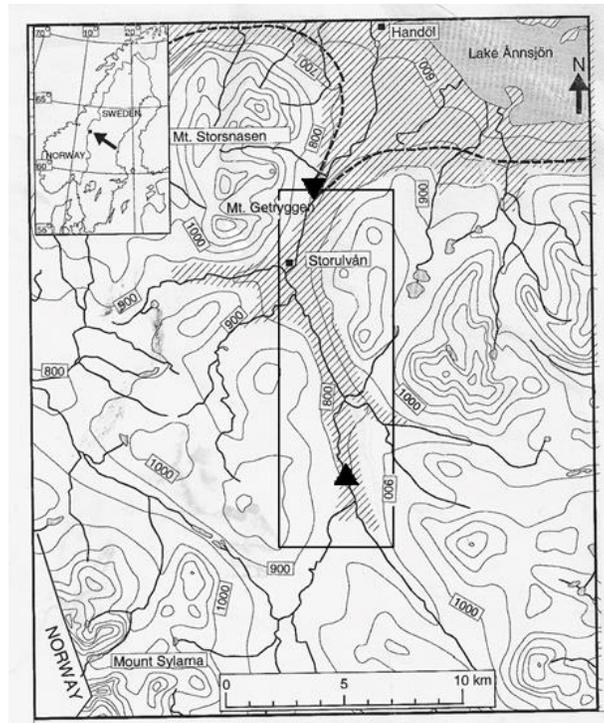


Figure 41. The pine treeline shifted about 12 km southwards between the black triangles over the period 1972-2022.



Figure 42 Left. The southernmost pine in the Handölan Valley, 800 m a.s.l. It germinated by the mid-1930s. Right. Its height has increased from 3.5 to 5 meter over the period 2013 to 2022. Photos: A. 2013-09-26. B. 2022-08-04.



Figure 43. Examples of vigorously growing pine trees which have recently emerged in the birch forest, above the pine treeline of the early 1970s (Fig. 46). They all established in the 1930s and 1940s. Left. Mt. Laptentjahke, 830 m a.s.l. Photo: 2013-05-31. Right. Mt. Västra Bunnerstöten, 820 m a.s.l. Photo: 2022-08-02



Figure 44. After the 2000's, prolific pine regeneration has taken place in the treeline ecotone, where pine stands became locally extirpated by cold conditions during the Little Ice Age. Apparently, pine is currently reclaiming territory hold during the Medieval Climate Anomaly. The tree pine in the background is about 320 years old. The upright stem, above the distinct "knee", dates to the early 20th century. Mt. Storsnasen, 680 m a.s.l. Photo: 2022-09-14. Source: Kullman & Öberg (2021).



Figure 45. Pine invading dense *Calluna*-heath in the lower birch forest belt. All saplings are 10-15 years old. Mt. Storsnasen, 680 m a.s.l. Photo: 2022-10-31.



Figure 46. Mature pine tree growing slightly below the treeline, encircled by cohort of young descendants, which have recently evolved to a tree stand. Mt. Storsnasen (650 m a.s.l.). Photo: Left. 1986-04-04. Right. 2017-04-26.

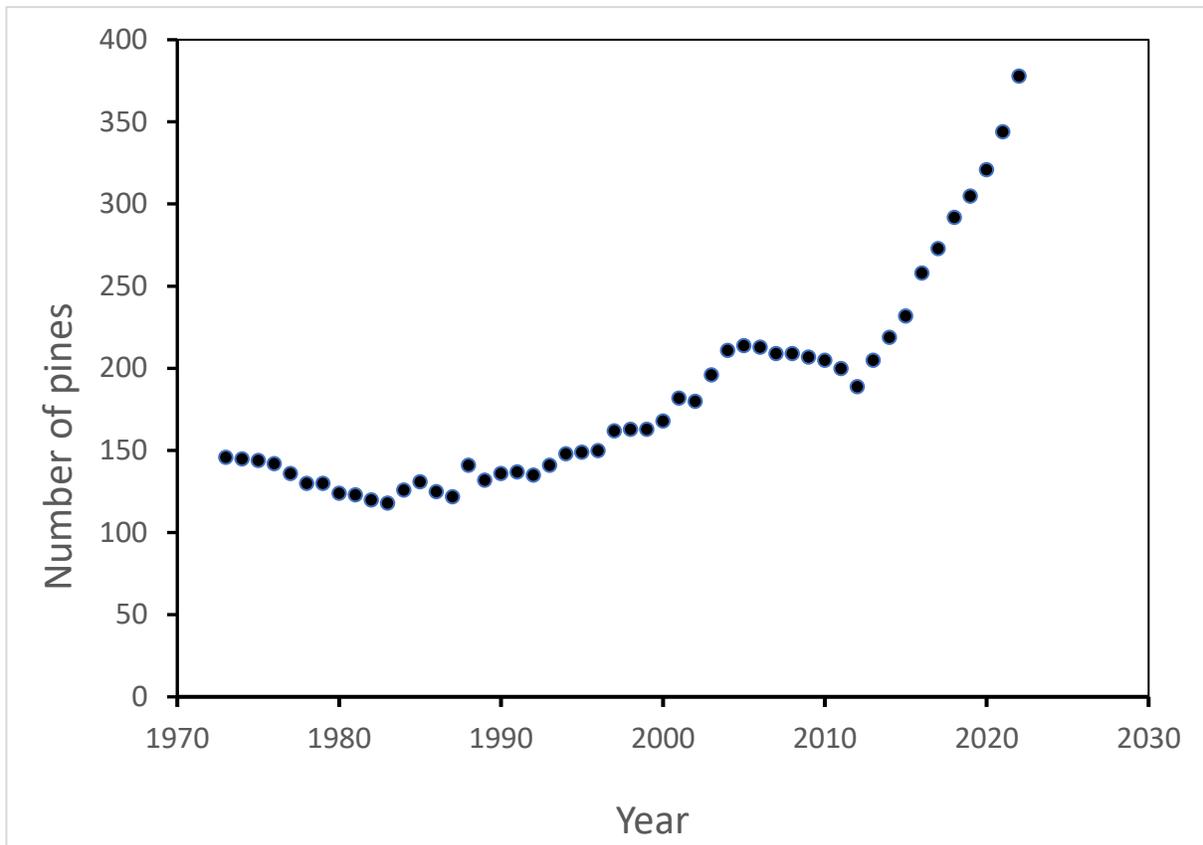


Figure 47. Evolution of pine demography annually surveyed within 18 permanent plots (10x10 m) over the period 1973-2022. Source: Kullman (2014, updated)

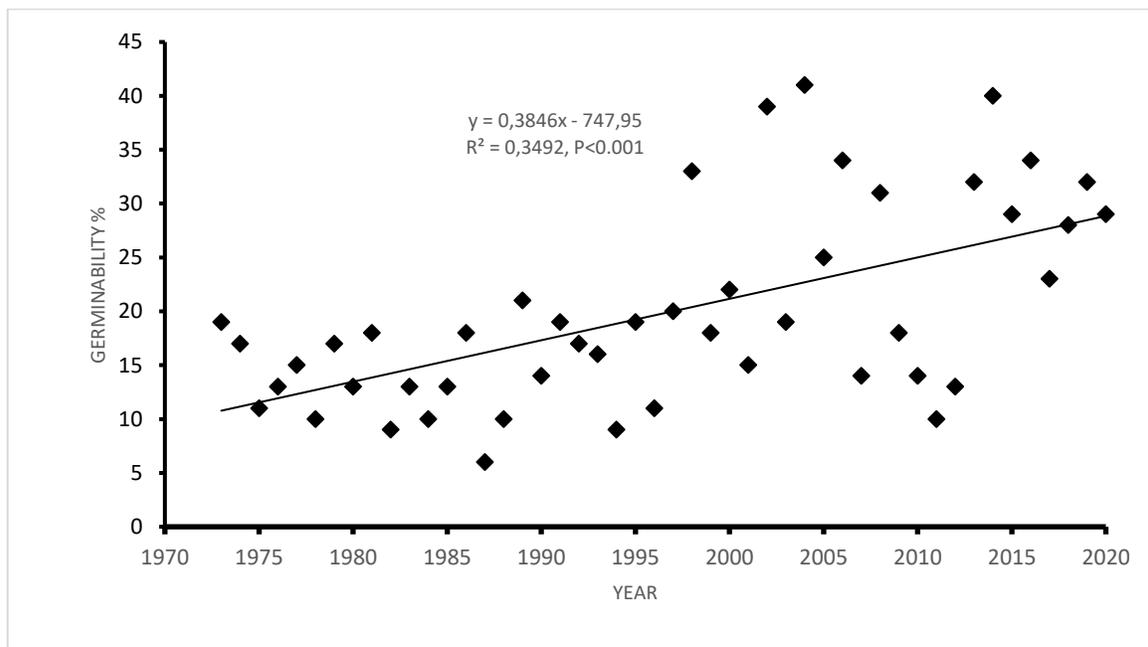


Figure 48. Annual records of (1973-2020) of pine seed viability from pines growing in the treeline ecotone. Source: Kullman (2019).



Figure 49. Close-up view of the ground cover of Figure 45. Predominant species are *Calluna vulgaris*, *Empetrum hermaphroditum* and *Betula nana*. Interspersed are patches with lichen fragments, resulting from reindeer grazing and trampling. Obviously, pine regeneration has gained from that kind of disturbance. Photo: 2022-09-14.



Figure 50. Drought-related dieback of a birch stand on a convex part of the local topography. Mt. V. Bunnerstöten, 820 m a.s.l. Photo: 2022-08-02.



Figure 51. Active thinning of a birch stand on a convex, snow-poor and drought-prone segment of the subalpine landscape facilitates the establishment of pine and possibly a gentle ecosystem transformation. Mt. Getryggen, 780 m a.s.l. Photo: 2022-08-13.



Figure 52. Vigorously regenerating birch stand at the fringe of the huge snow accretion (to the left), that has shrunk in recent decades. It contrasts with the snow free crests (to the right), where stand thinning and pine establishment take place at the present day (cf. Fig. 53). Mt. Getryggen, 780-805 m ö.h. Photo: 2016-05-02 .



Figure 53. Birch forest invading site with late-lying, although receding, snow cover, dominated by genuine snow bed plants, e.g. *Salix herbacea*. Mt. Storsnasen 710 m a.s.l. Photo: 2022-09-27.

POSITIONAL SECULAR ELEVATIONAL TREELINE CHANGE - EXTENT AND MECHANISMS DURING THE PAST 100 YEARS

Over the past 100 years, the Handölan Valley and adjacent mountains have been the focus of treeline assessments, based on observations with a standard methodology (Smith 1920; Kullman 1979, 1981a,b, 1986a,b; Kullman & Öberg 2009; Öberg & Kullman 2012). Based on these sources, average upshifts for birch, spruce and pine are displayed in Table 1. Birch and spruce have advanced by average c. 100 m. The maximum birch rise by 245 m (Fig. 54) complies with maximum displacement of treelines in widely different parts of the Scandes (Kullman 2021a), stressing that a regionally operating force, reasonably climate change, is the ultimate driver. Obviously, birch and pine have benefitted from their ability to regenerate phenotypically from a pool of pre-existing krummholz individuals. This has been the predominant mode of treeline advance by these species. Likewise, groves of birch trees above the treeline of the early 20th century are multi-stemmed cones with a common origin. Pine, in contrast, have to rely on seed regeneration. Its treeline is generally situated in the lower birch belt and as to compete with prevailing dense birch stands. Characteristic examples of raised treelines are provided by Figures 55-58.

Site-specific different treeline advances within an homogenous area, with respect to climate character and climate history, suggest that treeline responses to climate change are modulated and constrained by local topoclimatic conditions (cf. Kullman 1979; Kullman & Öberg 2009). Sites with the largest upshifts provide the most clearcut signal of response to altered climate (Kullman 2021a).

Upshifts of the birch forest-limit (1915-1975 have been substantially smaller than treeline advance over the same period of time and in the same area (Kullman 2022a). Average birch forest-limit advance is less than 20 m. Figure 59 provides an example from the study area of only subtle forest-limit advance over the past 100 years. Analogous results, showing modest upshifts, are reported from Norway and Finland (Holtmeier 2005; Rannow 2013; Hofgaard et al. 2015, Bandekar & Odland 2017; Bryn & Pothoff 2018). This circumstance casts some doubt on alarmistic projections proposing forest advance by 233-667 altitudinal meters by the end of the present century (Moen et al. 2004). Limited future advance of the forest-limit is projected also by Donato (2013).

Table 1. Average positions and species specific treeline upshifts (altitudinal meters), based on comparison between 1915 and 2022 on 25 mountain slopes, with different aspects, in the Handölan Valley. Source: Kullman & Öberg (2009, updated).

YR / Species	Treeline ± S.D. (m a.s.l.)	
	1 915	2022
Birch	846.25±48.68	936.04±199.33
Spruce	755.77±56.01	868.46±252.66
Pine	706.52±24.94	749.52±39.08



Figure 54. Left. Old-established birch, representing the treeline by the early 20th century (830 m a.s.l.) according to observations by Smith (1920). Photo: 1974-06-07. Right. Up to the present day, the treeline in that slope has shifted upslope to 1045 m a.s.l, i.e. a total displacement of 215 m over the past 100 years. Photo: 2022-07-31. Source: Kullman & Öberg (2018).



Figure 55. Predominantly, birch treeline advance is mediated by root suckers, creating millennial-old clonal groups of interconnected stems. This specific birch existed here about 4800 years ago, possibly as a low shrub. It transformed into tree-size in response to modern climate amelioration, which raised the treeline during the 20th century. Mt. Getryggen, 905 m a.s.l. Photo: 2022-07-31. Source: Öberg & Kullman (2012).



Figure 56. Outlier clonal birch stand, which developed tree-size and contributed to treeline to advance during the past 100 years. All stems originate from an old-established common centre. Initiation of stems peaked in the 1930s and 1940s. Photo: 2022-09-16. Mt. Storsnasen, 845 m a.s.l.. Source: Kullman (2007b)



Figure 57. Left. Clonal treeline spruce, which suffered extensive needle mortality in the 1970s. Photo: 1974-04-21 Right. Since the early 1990s, in accordance with milder winters and reduced incidence of frost desiccation, it has recovered remarkably. Photo: 2020-03-07. Mt. Storsnasen, 805 m a.s.l. Source: Kullman (2021c)



Figure 58. Spruce marking the treeline 1915. Smith (1920) noted this specimen as the spruce treeline around 1915. It suffered gradual canopy decline during the period 1974-2022, and obviously prior to that, in concert with somewhat lower temperatures after the optimum in the 1930s. Since about 2011, a distinct recovery has taken place by vertical advance of peripheral layering branches. Some of these new ramets have attained tree-size by 2022. Mt. Storsnasen, 790 m a.s.l. Source: Kullman (1983a updated). Photos: Upper left. 1974-06-06. Upper right. 2002-07-22. Lower left. 2011-09-20. Lower right. 2022-09-09



Figure 59. Distant view of the same mountain side in the Handölan Valley (Mt. Mettjeburretjahke) in the early 20th century and the present day. In both cases, the birch forest-limit is relatively sharp, and seems virtually unchanged in position over the past 100 years. Detailed study revealed an upslope shift by some tens of meters over the same period of time. In contrast, the treeline advanced by 125 altitudinal meters. Left. 1914-04-16. Right. 2017-04-17. Source: Kullman 2010.

ALPINE FLORA ENRICHMENT

Relying on older inventories from the 1950s (e.g. Kilander 1955), the alpine flora on some mountain summits in the concerned study area and elsewhere in the Scandes has become enriched in recent decades by upward displacement of genuine forest plant species, e.g. *Geranium sylvaticum*, *Maianthemum bifolium*, *Trientalis europaea* and *Melampyrum sylvaticum*. Average upslope advancement in the Swedish Scandes is 200 m and species enrichment on high alpine summits ranges 60-160 % since the early 1950s (Kullman 2004, 2007a,b, 2010a). Similar results are reported from Norwegian mountain areas (Klanderud & Birks 2003; Felde et al. 2012; Michelsen et al. 2011). Stunning appearances are the presence of tall herbs, forbes and tree saplings on high-alpine moraines (Figs. 60 & 61).

The pivotal role of climate variability for alpine flora dynamics is provided also by some marginal distributional recession of a few of the recently upshifted vascular plant species during some cooler and more snow-rich summers in the recent past (Kullman 2014a).

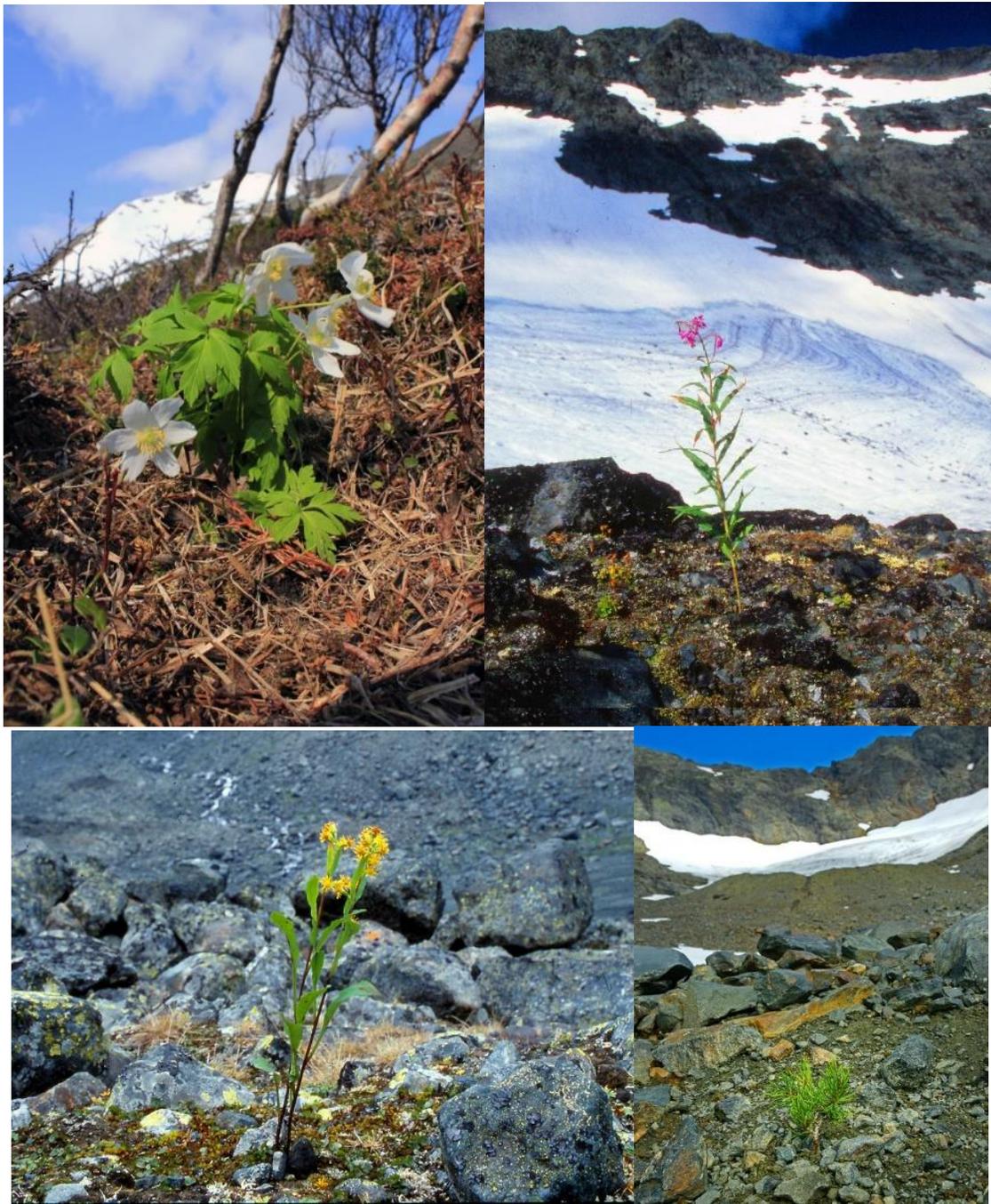


Figure 60. Invaders since the early 1950, to alpine grounds above the treeline. All are characteristic “forest dwellers”, now appearing on uniquely high elevations. Upper left. *Anemone nemorosa*. Mt, Storsnasen 845 m a.s.l. Upper right. *Epilobium angustifolium*. Mt. Sylarna 1440 m a.s.l. Lower left. *Solidago virgaurea*. Mt. Sylarna 1475 m a.s.l. Lower right. *Pinus sylvestris*. Mt. Sylarna 1350 m a.s.l



Figure 61. Rowan (*Sorbus aucuparia*) is dispersed by birds and it may adjust its vertical distribution quite rapidly to altered climatic conditions. Seed-sown sapling of rowan on a high-alpine moraine, about 600 m above its local treeline. Mt. Sylarna, 1465 m a.s.l. Photo: 2002-07-21.

SPREAD OF EXOTIC PLANT SPECIES

During the past few decades, plant species, not native to Sweden, the Scandes in particular, have become scatterdly established in Swedish mountain birch forests (Kullman 2020). Most conspicuous are young specimens of lodgepole pine (*Pinus contorta* var. *latifolia*), which in some cases have attained tree-size and reproductive maturity (Fig. 62). This species was introduced from Canada into forestry in the 1970s. Obviously, it has spread from trials close to the village Handöl. Another newcomer in the subalpine environment is stone pine (*Pinus cembra* ssp. *sibirica*), which has been planted as ornamental trees in villages near the mountains. From there, it has spread by seed caching nutcracker (*Nucifraga caryocatactes* ssp. *macrorhynchus*) to the transition between upper coniferous forest and mountain birch forest (Fig. 63).

It has been speculated that a warmer climate, in combination with a rising concentrations of CO₂ in the atmosphere might stimulate the spread of exotic tree species to new regions (Willis et al. 2010; Thomas 2013). As evident from Figures 62 and 663 a high mortality rate and frequent injuries caused by voles, hare and moose baize the prospect of extensive spontaneous spread of the concerned species on the mountain landscape.



Figure 62. Left. Lodgepole pine, established in the lower birch forest belt. Right. During the winter 2017/2018 it was ringbarked by voles and subsequently died. At the base of the dead stem, a young sapling has emerged. Mt. Storsnasen, 690 m a.s.l. Photos: Left. 2012-09-06. Right. 2022-09-20.



Figure 63. A bundle of stone pine saplings have germinated at the base of a 500-year old pine. After attack by voles in 2019, it gradually lost foliage and vigour, but seems to survive. Mt. Storsnasen, 685 m a.s.l. Photos: Left. 2019-09-0. Right. 2022-09-12.

FOREST FIRES

As in most parts of the boreal ecosystem (Zackrisson 1977; Engelmark & Hytteborn 1999), ecological disturbance by forest fires have occurred in the Handölan Valley (Kullman 1983a, 1996b, 2000). This aspect has not been studied in detail, although both natural and human-caused fires (mining and shieling practise) have occurred in the treeline ecotone prior to the 20th century (Fig. 64). In general, however, fire appears to have played a smaller role in the concerned ecosystem compared to boreal forests at lower elevations.

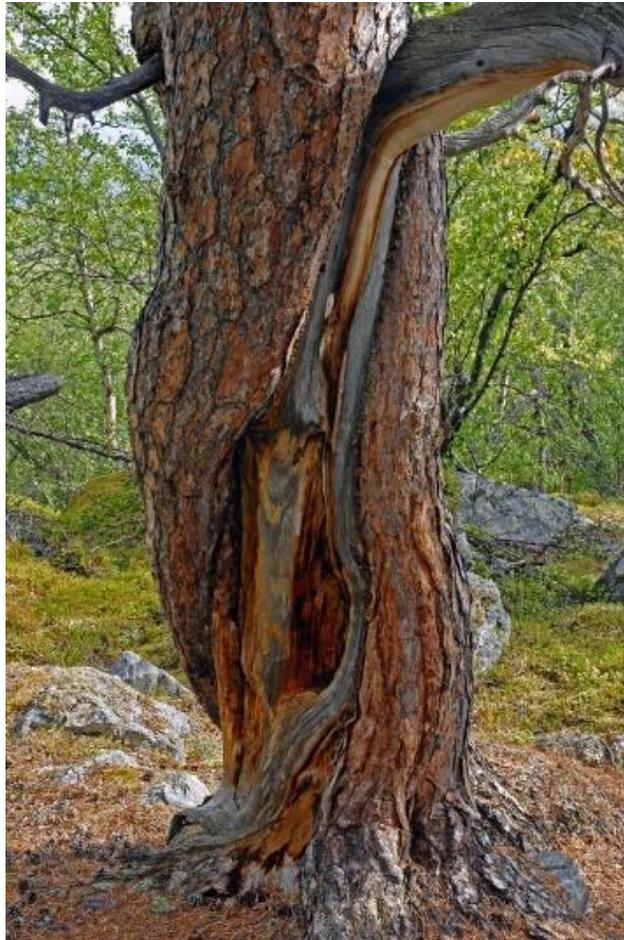


Figure 64. Pine, at least 400 years old, with fire scars indicating survival of 2 fires during the past 250 years. Mt. Norder-Tväråklumpen, 685 m a.s.l. Photo: 2009-08-22.

A SUBALPINE CULTURAL LANDSCAPE

Humans have utilized natural resources in the Scandinavian mountains for at least the past 10 000 years (Welinder 2009; Josefsson et al. 2016). Ecotonal landscapes have for long allowed subsistence for native people, relating to nearness to widely different ecological resources and services, offered by forest and open landscape, respectively (Taylor 1975; Emanuelsson 2009). The Scandinavian subalpine birch forest belt may, in some sense, be characterized as a culturally coined cultural landscape (Westerdahl 1980; Emanuelsson 1987; Aronsson 1998). Definitely, all of the total extent of the mountain birch forest is in no case primaeval wilderness, but for long, more or less affected by different kinds of human activity, concurrent with an ever fluctuating climate (Kullman 1975, 1976, 1979; Kullman 2016; Hofgaard 1997, 1999; Karlsson et al. 2007; Staland et al. 2010; Selsing 2010; Hörnberg et al. 2006, 2015; Josefsson, Bergman & Östlund 2016), the character of which will be outlined below.

It has been discussed whether the entire vertical extent of the subalpine birch forest belt is basically a natural phenomenon, but rather potential pine and spruce forest. In particular land use at the coniferous forest limit during cold periods (Little Ice Age) may have hampered regeneration of conifers, which favoured mountain birch (Sernander 1902; Hustich 1948; Blüthgen 1960; Rikkinen 1981; Kullman 1976, 1981 a, b, 2016a).

In particular, the Sami culture, has since at least 1000 years by tradition upheld a particular and close relationship with the treeline ecotone (Ruong 1975; Emanuelsson 1987), initially by reindeer hunting, eventually transforming into intensive reindeer herding, which peaked from the 17th to the late 19th century. Thereafter, reindeer pastoralism became more extensive, i.e. larger herds were roaming more freely over wider areas.

Reindeer (wild and semi-domestic) are an integral part of the ecosystem, contributing to its structure, composition and continuous dynamics. Prior to the onset of extensive herding by the 1920 or so, dwelling sites were often located to the upper mountain birch forest, with resulting forest clearings and grazing and other activities in the neighbourhood (Figs. 65-71).

It appears that a profound ecological and human subsistence shift occurred around 4000 cal. a BP, as a cooler, more snow rich and more instable Neoglacial climate evolved (Larsson et al. 2012; Kullman 2013). This circumstance favored life of reindeer versus moose and imposed a fundamental change of human use of the landscape.



Figure 65 During the summer, reindeer preferentially graze the high mountains above the treeline, in order to avoid the heat and harassing insects. Mt. Getryggen 1360 m a.s.l. Photo: 2013-07-12.

The number of semi-domestic reindeer has increased substantially during the past 100 years in the study region (Kullman 2017b). As previously commented, that process parallels climate warming and it is therefore conceivable that climate warming and increased reindeer impact mutually promoted vegetation progression, treeline rise in particular. Landscape-scale thinning of the extant plant cover (lichens in particular), by free-roaming reindeer is well documented may in the southern Scandes during the past 100 years (Smith 1920; Allard 2003; Kullman 1989d, 2004). This mode of ecological disturbance may have facilitated the establishment and growth of tree saplings (Fig. 74). In the case of pine, this mechanism is quite obvious since reindeer reduce prevailing lichen carpets, thus breaking the "lichen barrier

effect” (cf. Holmgren 1912; Tømmervik et al. 2009; Kullman 2017b), thereby facilitating establishment of trees.



Figure 66. Within the treeline ecotone, extensive and continuously increasing reindeer grazing during the past 100 years, has virtually extirpated reindeer lichen mats, previously interspersed within stands of *Empetrum hermaphroditum*, *Arctous alpina* and *Betula nana*. This process has promoted regrowth of pine, which had become demised during the Little Ice Age. Mt. Storsnasen, 690 m a.s.l. Photo: 2022-09-14. Source: Kullman & Öberg (2021).



Figure 67. Pitfalls of various ages, indented for reindeer and moose, are indications of ancient and organized use of natural resources in the treeline ecotone. Mt. Getryggen, 745 m a.s.l. Photo: 2017-06-17.



Figure 68. Left. Mountain birch forest thinned by Sami cuttings. As a consequence, *Juniperus communis* has gained from the lighter conditions. Mt. Tjallingklumpen, 810 m a.s.l. Photo: 2013-09-26. Right. Large gap in the birch forest, with a plant cover dominated by herbs and grasses. Primarily, this kind of vegetation was shaped by excessive snow cover, but later on maintained by reindeer herding. Reforestation use to be very sluggish, even in the warmer climate during the past 100 years. Mt. Lapentjahke, 760 m a.s.l. Photos: 2022-08-05.

Overall, treeline positions have been relatively little negatively affected by reindeer grazing. That supposition draws on the "Principle of Least Effort", which states that the extraction of natural resources in general diminishes towards their upper margin, where the cost and efforts exceed the potential gains (Shackleton & Prins 1992).

Concerning the treeline in general, there is no firm evidence that the birch treeline position has been lowered due to human impact in the past (Kilander 1965; Kullman 1975, 1976, 1979, 2016; Kjällgren & Kullman 1998; Gunnarsson et al. 2012; Alatalo & Ferrarini 2016).



Figure 69. Ongoing marginal birch regrowth of an abandoned reindeer paddock. Mt. Lapentjahke, 740 m a.s.l. Photo: 2010-06-11.



Figure 70. Clearing of mountain birch forest has facilitated the spread and establishment of conifers, in this case spruce. Mt. Tjallingklumpen, 805 m a.s.l. This is the southernmost spruce tree in the Handölan Valley and has attained tree size after the 1950s. Photo: 2013-09-26



Figure 71. A former clear-cut Sami dwelling site, used until the mid-1920s, with some large birches left over in order to promote some shade and coolness to the animals. Currently, birch is regaining its previously dominant role at this site. Mt. Getryggen. 745 m a.s.l. Photo: 2010-06-11

In addition to reindeer pastoralism, the subalpine forest and the lower alpine belt, have been utilized by local farmers for summer livestock grazing, hay making, wood cutting, leaf fodder and lichen gathering for the winter (Figs. 72-74). This shieling practice (sw. fäbodbruk) has its roots in the Iron Age, about 1000 years ago, but in the study area the earliest records of summer farms refer to the first half of the 19th century. The use of shielings ceased by the 1940s or

earlier. In general, these summer farms were located several kilometers from the sedentary farms and often at the interface between coniferous and mountain birch forest (Kilander 1942). Mires and meadow birch forests were used and manipulated for hay production, while more poor forest communities were grazed (Kullman 1979, 2016a). The effects of these land use practices are still perceivable on the landscape scale. As a consequence, a rich, luxuriant and appealing ground flora evolved, particularly at the final phase of utilization. At the present, these “botanical Edens” gradually disappear in the wake of abandonment and forest regrowth, which deeply engages nature conservation authorities, although the applied measures may seem controversial (Kullman 2016b).



Figure 72. Hay barn belonging to the sheiling Väster-Dalsvallen, 5 km to the south of the village Handöl, 760 m a.s.l. This summer farm was established in 1829 and discontinued in the 1940s. Photo: 2022-08-18.



Figure 73. Previously clear-cut area in the near vicinity of Väster-Dalsvallen. Vigorous regrowth of birch after the abandonment in the 1940s. Photo: 2022-08-18.



Figure 74. Remnant stout birch at the margin of stand displayed in Figure 76. Coring at the base provided an age of 260 years. Photo: 2022-08-18.

The subalpine and upper coniferous forests in the study area, and elsewhere in the Scandes, have been affected by mining activities since the 17th century. As depicted below (Figs. 75-77), these practices have affected the tree cover in the surroundings, by extensive wood cutting with long-lasting effects on the landscape structure, as evidenced also in other parts of the Scandes (cf. Selander 1950; Zackrisson 1985). Since mining was carried out during relatively cold centuries of the Little Ice Age, reforestation has been slow and incomplete, despite improved climatic conditions.



Figure 75. The entrance to the Handöl copper mine, 660 m a.s.l. The surrounding birch dominated landscape is largely a consequence of mining activities, which consumed pine stands within a circumference of some kilometers. Photo: 2021-09-08.



Figure 76. A small hillock, visible in the distant upper part of Figure 84. Prior birch and pine stands have been clear-cut and the soil layer removed in connection with prospecting for possible mining resources. Mt. Storsnasen, 650-670 m a.s.l. 2019-09-07.



Figure 77. Solitary pine tree (205 years old) in a landscape more or less deforested by conifers in connection with mining activities. The mouth of the Handölan Valley, 645 m a.s.l. Photo: 2022-09-21.

SUMMARY

This study with main focus on multi-temporal change and related dynamics of the treeline ecotone. It provides an observational narrative broadly representative of the Swedish Scandes.

Deglaciation of exposed nunataks occurred already 17 000-13 000 cal. a BP, which is much earlier than previously assumed. During this interval, as evidenced by megafossil analyses, birch, pine and spruce appeared on ice free mountain summits and at sites of rapidly vanishing glaciers, 600- 400 meters above their current treelines. Postglacial climate warming peaked prior to 10 000 cal. a BP, with summer temperatures about 3 °C higher than today (early 21st century). Thereafter, in a climate more favourable than present, the glacier ice in the valley bottoms gradually shrank and finally disappeared, supporting a landscape, richer and more biodiverse than conventionally inferred. Eventually, trees and other plants were enabled to

spread downslope. Shortly after the thermal optimum, slight cooling was initiated, which by c. 6000- 5000 cal. a BP had reached a point when glacier reappearance was initiated (Neoglaciation). Concomitantly, a long-term extirpation process of the highest tree enclaves (mostly pine) and scattered stands of thermophilic broad-leaved tree taxa prevailed; *Quercus*, *Ulmus*, *Corylus*. This cooler, moister, more snow rich and variable climate (*borealization*), paved the way for expansion of the subalpine birch forest belt, as we know it today. Moreover, general spread and increased abundance of spruce occurred, while Siberian larch was totally extirpated. # The Neoglacial climate deterioration and ensuing generic vegetation recession were temporary halted during the “Mediaeval Climate Anomaly”, about AD 1000-1300, when treelines turned upslope by at least 100 m, relative to the early 21st century.

The favourable mediaeval climate was followed by resurgence of the Neoglacial cooling trend, which culminated with the “Little Ice Age” (AD 1300-1900), when mountain glaciers expanded to their largest sizes since the last glacier epoch. Concurrently, extensive forest dieback occurred in the mountain region, and alpine treelines were depressed to their lowest postglacial positions.

With a gentle onset by the mid-19th century, the modern and still prevailing phase of climate warming took place, for reasons not fully understood. Climate improvement peaked in the late 1930s, halted for some decades and has subsequently, with short-term interruptions, remained at a fairly high level.

Consequent on the most recent warming phase, treelines of dominant species have raised higher than during the Mediaeval Climate Anomaly and have reached their highest positions over the past 7000 years. Concurrently, the alpine vascular plants flora has gained in species richness by upwards encroachment of genuine “forest plant species”, without any loss of genuine high-alpine species.

Observed changes signal a profound transformation of the alpine landscape and the treeline ecotone, given that the warming trend continues. A most radical change may be the emergence of a pine-dominated subalpine forest belt, at the cost of the mountain birch forest.

The landscape-ecological changes, highlighted in this study, are well within the frames of natural dynamics during the Holocene epoch, which contrasts with common climate catastrophe rhetoric.

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