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Higher-than-present Medieval pine (*Pinus sylvestris*) treeline along the Swedish Scandes

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Abstract

The upper treeline of Scots pine (*Pinus sylvestris* L.) is renowned as a sensitive indicator of climate change and variability. By use of megafossil tree remains, preserved exposed on the ground surface, treeline shift over the past millennium was investigated at multiple sites along the Scandes in northern Sweden. Difference in thermal level between the present and the Medieval period, about AD 1000-1200, is a central, although controversial, aspect concerning the detection and attribution of anthropogenic climate warming. Radiocarbon-dated megafossil pines revealed that the treeline was consistently positioned as much as 115 m higher during the Medieval period than today (AD 2000-2010), after a century of warming and substantial treeline upshift. Drawing on the last-mentioned figure, and a lapse rate of 0.6 °C/100 m, it may be inferred that Medieval summer temperatures were about 0.7 °C warmer than much of the past 100 years. Extensive pine mortality and treeline descent after the Medieval warming peak reflect substantially depressed temperatures during the Little Ice Age. Warmer-than-present conditions during the Medieval period concur with temperature reconstructions from different parts of northern Fennoscandia, northwestern Russia and Greenland. Modern warming has not been sufficient to restore Medieval treelines. Against this background, there is little reason to view further modest warming as unnatural.

Keywords:

treeline, *Pinus sylvestris*, climate change, megafossils, Little Ice Age, Medieval Warm period, Swedish Scandes

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1 Introduction

The current scientific and public concern about future climate change and associated geocological transformations draws on unvalidated General Circulation Models (IPCC 2007). Their failure to convincingly account for stalling global temperature evolution since the late 1990s (Akasofu 2013; Tollefson 2014) indicates incomplete systemic understanding, which argues for more extensive inclusion of robust historical data as a prerequisite for realistic modelling of climate evolution and associated biological consequences (Humlum et al. 2011). The importance of putting present-day change into a wider temporal context of previous climate and ecosystem variation cannot be overstated (cf. Zwiers & Hegerl 2008). Ideally, such an effort can be accomplished by studying the history of the upper treeline, whose natural position and dynamism in principle relates to prevailing temperatures (Tranquillini 1979; Holtmeier 2003; Körner & Paulsen 2004).

The sensitivity of the treeline to climate change is empirically demonstrated by broad-scale upshift in close association with predominant climate warming over the past 100 years in widely different parts of the world (e.g. Moiseev & Shiyatov 2003; Lloyd 2005; Kullman & Öberg 2009; Harsch et al. 2009; Mazepa et al. 2011; Kirilyanov et al. 2012). Treeline rise by about 200 m (1915-2007) in the Swedish Scandes, as estimated by Kullman & Öberg (2009), is virtually what should be expected from recorded summer temperature rise by 1.4 °C and assuming a lapse rate of 0.6 °C/100 m. Thus, there is compelling evidence that the position of the upper treeline performs in a sub-centennial-scale dynamic equilibrium with climate evolution, indicative also of profound effects on high-mountain biota (Kullman 2010a, 2012).

By focusing on elevational treeline change over the past 1000 years, an assumedly wide spectrum of natural climate variability may be assessed. This time span goes from the Medieval Warm Period around AD 1000 (Lamb 1982; Ljungqvist et al. 2012) to the tail of the Little Ice Age about 100 years ago (Lamb 1982; Grove 1988; Matthews & Briffa, 2005). Climate change and variability over

this entire interval, in particular its possible global extent, homogeneity and magnitude, are central and somewhat controversial aspects with bearing on the current discourse concerning the range and impacts of human-induced future climate change (Crowley & Lowery 2000; Broecker 2001; Bradley et al. 2003; Esper & Frank 2009; Melvin et al. 2012). Aside of a political/ideological side (cf. Bradley et al. 2003; Esper & Frank 2009), this debate suffers from lack of robust paleoclimate methods and global coherence of available data. In particular, extensively used paleoclimate reconstructions from northern Fennoscandia are based on tree-ring data, analyzed by different and complex methods, without consideration for sample altitude, which tend to underestimate natural climate variability (Lindholm et al. 2010; Esper et al. 2012). These efforts have yielded conflicting inferences concerning the thermal level of the Medieval Warm Period and the Little Ice Age in this region as well as globally, relative to the past century (Briffa et al. 1990, 1992; Crowley 2000; Grudd 2008; Gunnarson et al. 2011; Melvin et al. 2012; Kaufmann et al. 2009; Kobashi et al. 2011; Ljungqvist et al. 2012). If science cannot agree on regional and global climate change over the past 1000 years and the underlying mechanisms, then it would be premature to launch models prescribing the course of climate throughout the 21st century.

Against this background, the present paper is a regional contribution to the building of a global-scale understanding of climate and ecosystem evolution over the past millennium. In addition, a paleotree-line reconstruction for this particular time slice may serve as an analogue for the dynamics and structure of high-mountain ecosystem in a potentially warmer future.

Drawing on different lines of proxy data (Hiller et al. 2001; Grudd 2008; Kullman 2013; Rinne et al. 2014), the main hypothesis to be specifically tested is that the pine (*Pinus sylvestris* L.) treeline (defined below) in northern Fennoscandia and adjacent regions was consistently higher than present (AD 2000-2010) about AD 1000-1200 (Medieval Warm Period). Thereafter it is assumed to have declined substantially in concert with Little Ice Age climate cooling.

2 Study area and modern treeline zonation patterns

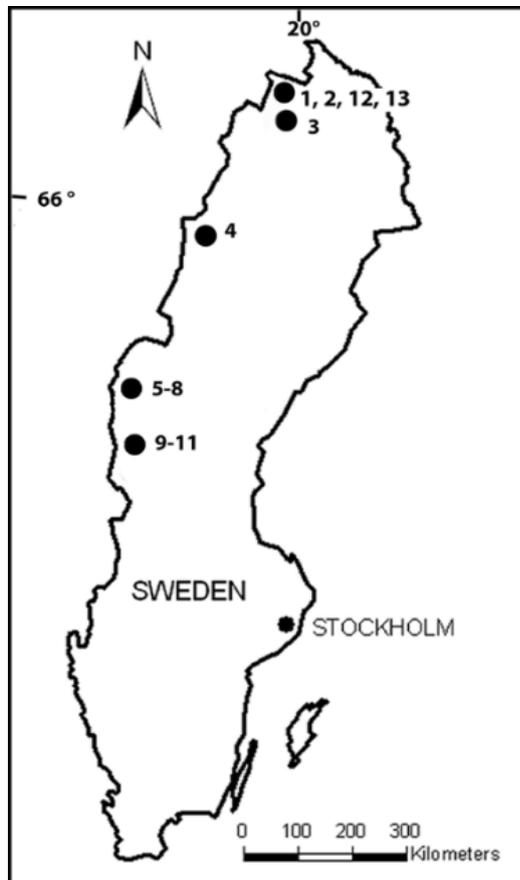


Figure 1: Location map showing the positions of the sampling sites along the Scandes in the northern half of Sweden. Numbers refer to Table 1.

Sampling spans a latitudinal range ($68^{\circ}24'N$ - $62^{\circ}03'E$) covering virtually the entire north-south extension of the Scandes in Sweden, between the provinces of Lapland, in the north, and Dalarna, in the south (Fig. 1). The valleys and mountain sides are covered with an upper subalpine forest belt and a treeline of mountain birch (*Betula pubescens* ssp. *czerepanovii*) adjacent to the alpine tundra. With great local variations, scattered specimens of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) form their respective treelines, around 100 and 50 m below that of the mountain birch and usually as outliers within the birch belt (Kjällgren & Kullman 2002). The present-day (2010-2013) local treelines of pine, set by the uppermost trees > 2 m tall (Fig 2), grade between c. 500 m a.s.l. in the north

and 1000 m a.s.l. in the south. As a rule, the ground cover around the pine treeline is dwarf-shrub heath, with *Empetrum hermaphroditum*, *Betula nana* and *Calluna vulgaris* as dominating species, sometimes intermixed with reindeer lichens (*Cladina* spp.). In contrast to the upper limit of closed pine stands, the treeline is insignificantly altered by past and present land use or fire (Kullman 1981; Kjällgren & Kullman 2002). Since the first decade of the 20th century, the pine treeline has shifted upslope by a maximum of about 200 m (Fig. 2), in concert with a summer warming trend of $1.4^{\circ}C$ (Kullman & Öberg 2009).

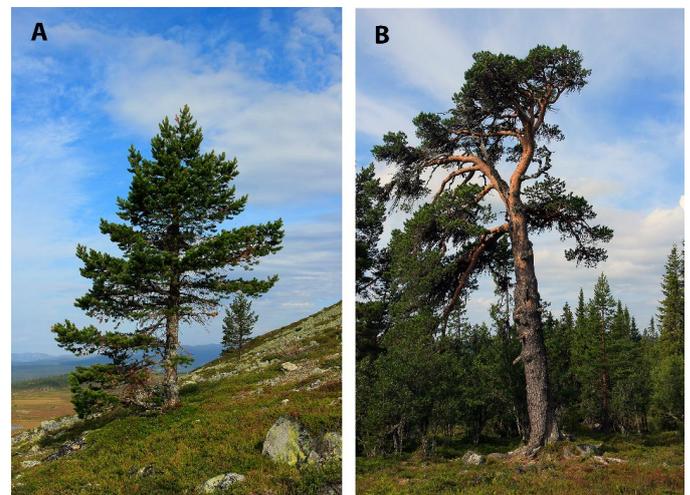


Figure 2: Present and past pine treeline of Mt. Djupgravstöten (province of Dalarna). A. Pine trees established in the late 1920s and representing treeline advance by 120 m in elevation. B. The early-20th century treeline, reconstructed at the present-day, in the form of and old-growth stout pine. Photo: Leif Kullman 27 June, 2013.

3 Methods

It is widely recognized that treeline positions primarily relate to summer temperature (e.g. Körner and Paulsen, 2004). Thus, shifts in treeline elevations are used in this study as proxy indicators of low-frequency paleoclimate history (cf. Karlén & Kuylenstierna 1996; Tinner & Kaltenrieder 2005; Kirilyanov et al. 2012; Kullman 2013), drawing on a conventional temperature lapse rate of $0.6^{\circ}C$ per 100 m in altitude (Laaksonen 1976). However, the discontinuous nature of megafossil records precludes high-resolution time series. A particular caveat

associated with historical treeline reconstructions based on megafossils is that any record represents a minimum elevation constraint for the contemporary treeline position. Another complication, according to conservative generalizations based on ring counts, is that large treeline pines may attain individual ages of 700-800 years, but usually somewhat less (Bartholin & Karlén 1983; Engelmark & Hofgaard 1985; Kullman 1994). This implies that radiocarbon-dating may yield widely different ages, depending on which part of a trunk that is dated. In most of the present cases, only the outermost and youngest parts were available for dating. Thus, the obtained ages are likely to post-date the establishment phase by some hundred years.

Primarily, this study is based on analyses of radiocarbon-dated megafossil remnants of Scots pine (*Pinus sylvestris* L.), identified within a zone 100-115 m above the modern (AD 2013) treeline along the entire Swedish Scandes. Megafossils refer to remains of trunks of formerly tree-sized specimens, which are found very close to their growing sites. Specimens lying more or less exposed on dry ground were specifically sampled, since this category of remnants is experienced to yield dates within the time interval concerned in this study (Bartholin and Karlén 1983; Kullman 2013).

The upper treeline (both past and present) is a central aspect of this study and is defined as the extreme elevation of erect pine trees, more than 2 m in height. For further elaboration of this concept and its ecological correlates, see Kullman (2010b).

As a complement to the study of upper pine treelines, “inverted” treelines (cf. Holtmeier 2003) against treeless subalpine heaths in valley bottoms, were scrutinized for the presence of megafossils. These conspicuous elements of the mountain landscape are characterized by a dense pattern of cryogenic non-sorted circles and underlying permafrost. The nature and genesis of these treelines and their relations and responses to climate and climate change are debated (Josefsson 1988; Becher et al. 2013). It is hypothesized here that their late Holocene performance mirrors that of the upper treeline as climate-driven components of the cold-marginal landscape.

Eye-witness accounts of stand-level demise near and in a zone below the treeline, during the final phase of the Little Ice Age, i.e. 19th and early 20th century, was obtained from systematic survey of contemporary geobotanical literature and itineraries.

Radiocarbon dating was performed by Beta Analytic Inc., Miami (USA). Radiocarbon ages are calibrated to calendar years before present (cal yr BP), with “present” = 1950 AD. Calibration was conducted by use of the INTCAL09 database (Reimer et al. 2009). In the text, the calibrated ages are quoted as the intercept values of radiocarbon ages with the calibration curve. Dating was carried out after pretreatment with standard laboratory procedures, including acid/alkali/acid wash.

Species identification of the recovered megafossils was unambiguous, due to remaining bark fragments. Altitudes (m a.s.l.) and geographical coordinates for the sites of all retrieved tree remains were obtained by a GPS navigator (Garmin 60CS), repeatedly calibrated against distinct points on the topographical map. Reported altitudes are rounded off to the nearest 5 m.

4 Results

A total of 37 pine megafossils, meeting the prescribed criteria, were recovered within the focused elevation band. Of these, a subsample of 13 specimens was dated, embracing the entire extent of the Swedish Scandes from north to south (Fig. 1.). It is virtually unknown whether these tree remains represent widely scattered trees or more dense stands. In some districts, however, wood of this kind has been systematically gathered by local residents for fire wood (e.g. Bartholin and Karlén, 1983). This circumstance could argue for stands denser than indicated by the current sparse spacing of megafossils exposed on the ground surface.

Both Medieval and present-day treeline positions display a strong rising tendency, north to south, in the study region, as expected for a treeline, constrained by macroclimatic heat deficiency (Cogbill & White 1991; Kjällgren & Kullman 2002; Holtmeier 2003).

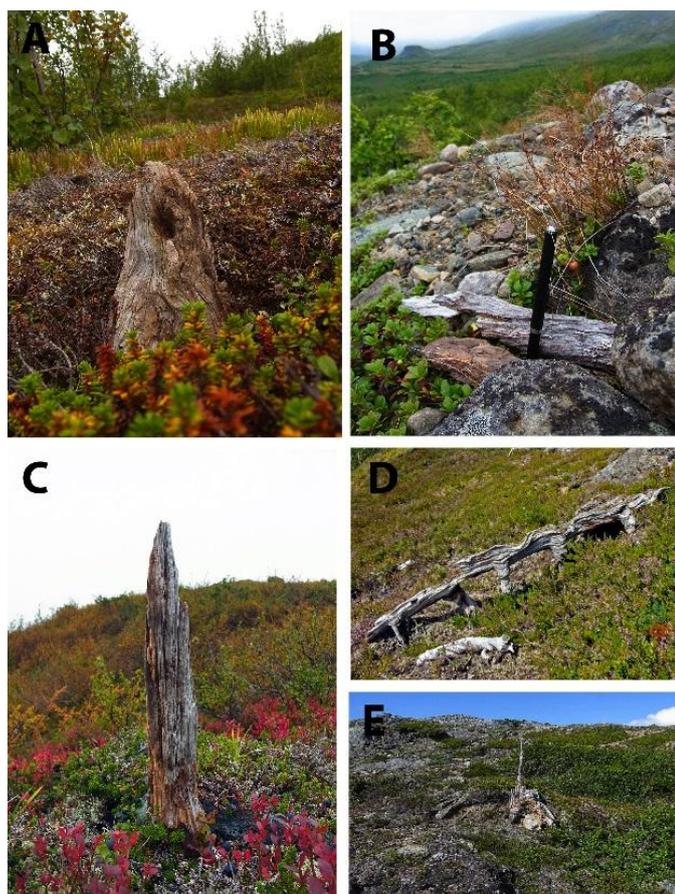


Figure 3: Examples of dated pine megafossils recovered above the current treeline. Numbers refer to Table 1. A. Njulla (1). B. Dalfälcorru (3), C. Njerubäive (5). D. Tjallingklumpen (8), F. Täljstensvalen (6).

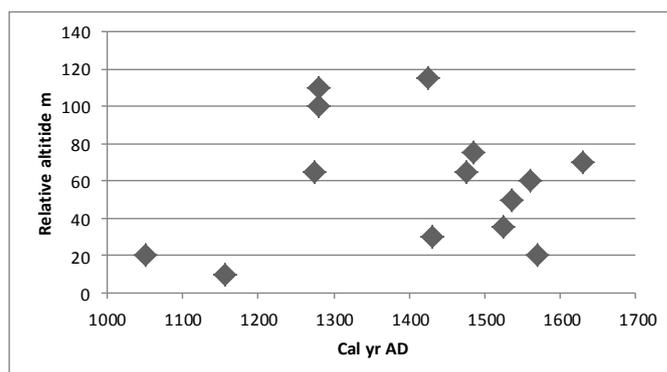


Figure 4: Radiocarbon-dates (intercept values) of all recovered pine megafossils and their relations to present-day altitude (m a.s.l.) of the pine treeline.

The obtained dates illustrate that higher-than-present treelines prevailed between AD 1050 and 1650, with an overweight in the record at the mid of this interval (Table 1, Figs. 3, 4). By the early 14th and early 15th century, the treeline peaked 100-120 m above the present position. Given a modal pine life-expectancy of 400-500 years (see above), it is reasonable to assume that the dated pines became established during the Medieval period, AD 1000-1300. This inference is supported by the heavily decayed nature of most specimens (Fig. 3).

Table 1: Radiocarbon dates of megafossil pine tree remains and their altitudes relative to the present-day (2013) treeline at the respective locality.

Age (¹⁴ C yr BP)	Cal yr AD 2σ	Cal yr AD Mid-point 2σ	Sample altitude (m a.s.l.)	Treeline 2013 (m a.s.l.)	Relative altitude (m)	Locality (no.)	Coordinates N lat.; E long.
270±30	1510-1750	1630	580	510	70	Njulla (1)	68° 21.829'; 18° 44.780'
710±30	1270-1290	1280	610	510	100	Slåttatjåkka (2)	68° 20.435'; 18° 42.971'
370±30	1450-1520	1485	585	510	75	Slåttatjåkka (2)	68° 20.209'; 18° 42.649'
480±30	1410-1440	1425	685	570	115	Darfälcorru (3)	67° 52.072'; 18° 38.147'
720±30	1260-1295	1280	680	570	110	Kebnetjåkka (4)	67° 52.041'; 18° 40.147'
320±30	1470-1650	1560	630	570	60	Kebnetjåkka (4)	67° 51.945'; 18° 37.057'
490±30	1410-1445	1430	720	690	30	Njereubäive (5)	65° 45.972'; 15° 20.790'
850±60	1030-1280	1155	770	760	10	Täljstensvalen (6)	63° 14.568'; 12° 27.564'
380±30	1440-1610	1525	870	835	35	Laptentjakke (7)	63° 08.351'; 12° 25.002'
410±30	1440-1510	1475	870	805	65	Tjallingklumpen (8)	63° 05.089'; 12° 28.158'
1000±70	900-1200	1050	780	760	20	N. Tväråklumpen (9)	63° 12.272'; 12° 22.151'
720±30	1260-1290	1275	1015	950	65	Ö. Barfredhågna (10)	62° 03.709'; 12° 24.447'
390±30	1440-1630	1535	1000	950	50	Ö. Barfredhågna (11)	62° 03.654'; 12° 24.277'
300±30	1490-1650	1570	1010	990	20	Djupgravstöten (12)	62° 03.187'; 12° 28.021'
830±30	1160-1260	1210	360	510	-150	Abisko-heath (13)	68° 21.527'; 18° 48.706'

Following this period, trees died consistently during subsequent centuries, particularly during the 14th century, and virtually without producing offspring, which could attain tree-size and preservation until the present. The overall outcome of this course was a general treeline lowering to a position, 2013 on average 60 m (range 10 - 115 m) lower than during the Medieval Period. Analogously, this study revealed a pine megafossil emerging by frost heave in the center of a non-sorted polygon, in a treeless subalpine heath (inverted treeline) well below the upper upper pine treeline (Fig. 5, Table 1). Radiocarbon-dating yielded an age of AD 1220 and a presumed establishment during the 12th century or even earlier.



Figure 5: Subalpine heath with non-sorted circles close to Lake Torneträsk by Abisko in northern Lapland. Near the centre of the circle, a small megafossil pine remnant is exposed by frost heave. Radiocarbon-dating yielded AD 1220: Photo Leif Kullman, 14 September 2013.

5 Literature survey

Appendix I is a list of 33 published papers from northern Sweden and adjacent regions of Finland and Norway, which quite unanimously account for treeline and upper forest demise and elevational retraction during the final phase of the Little Ice

Age and somewhat earlier. A preponderance of dead and dying trees, in combination with virtual no regeneration, is stressed in most of the reports. In many cases, a colder climate was explicitly assumed to be the primary reason.

Swedish forest authorities were well aware of the situation and feared an imminent and widespread alpine tundra expansion over high-lying forest regions, which prompted implementation of restrictive legislation concerning logging in marginal forests (Andersson 1906). An expression of the dire situation was that one of the first national parks in the Swedish Mountains, Sonfjället, was established (1909) with the outspoken purpose to create an arena for scientific study of ongoing treeline descent (Öberg 2009). Still today, large pine snags, reasonably representing Little Ice Age mortality and slow demise, following a more favourable climatic situation than present, are met with in the alpine tundra or upper sparse mountain birch forest of this national park and other districts (Fig. 6).



Fig. 6. Pine snag with more than 500 tree-rings and which obviously died during the Little Ice Age. Today, living pines of this dimension do not exist, neither at this elevation nor at the current treeline. Mt. Sonfjället, 875 m a.s.l. Photo: Leif Kullman, 10 June 2008.

6 Discussion

The relative small number of dated megafossils precludes any detailed discussion and regional differentiation of the obtained results.

Consistently for the entire range of the Swedish Scandes, the pine treeline, represented by the dated megafossils, was significantly higher than present during the Medieval period, although declining in altitude throughout the subsequent Little Ice Age. Over the latter epoch, the uppermost pine trees died commonly and the final of this protracted process could be witnessed about 100 years ago, as explicitly evident from the literature survey. Assuming that most of the dated pines had become established 200–300 years prior to the assigned death year (Table 1) (cf. Karlén 1996) makes it reasonable to assume that the majority of the demised trees had originated from the Medieval period around AD 1000–1300. Thus, the altitude (m a.s.l.) of the uppermost radiocarbon-dated pines is tentatively taken as a minimum elevation for the Medieval treeline. Presumably, pine trees may have prevailed at even higher elevations without leaving visible traces. The climatic favourability of this period is further indicated by concurrent pine growth in treeless environments (inverted treeline), 150 m below the upper pine treeline, currently characterized by non-sorted polygons and permafrost and totally devoid of pines and tree birches.

Obviously the Medieval epoch offered the most conducive climate for high-elevation pine tree growth and regeneration during the past 1000 years or so. Summer climate warming by c. 1.4 °C and common regional treeline rise since the early 20th century (Kullman & Öberg 2009) has not been enough to push the treeline the whole way everywhere back to its Medieval position (Kullman 2013, 2014).

Since the present-day treeline has been shifted upslope in near-equilibrium with 20th century climate warming along the Swedish Scandes (Kullman & Öberg 2009; Öberg & Kullman 2011), it is reasonable to assume that modern treelines are in a dynamic near-equilibrium with the prevailing climate. Thus, there is no substantial lag in the sense

that the present-day treeline should be located far below its potential position. This responsiveness is a prerequisite for accurate summer temperature reconstructions concerning the difference between Medieval and modern summer temperatures.

As indicated above, the field-sampling procedure tends to yield minimum values of past treeline elevations. Moreover, the Medieval treeline position may be underestimated since relatively small and young trees representing short-term warming spikes have possibly not been preserved until the present. Therefore, and for the purpose of climate reconstruction, the largest recorded difference between Medieval and present treeline is used, i.e. 115 m. By drawing on a lapse rate of 0.6 °C per 100, a Medieval period, at least 0.7 °C warmer than the past few decades may be computed. A similar magnitude of change is inferred from treeline and dendroecological studies at a site in the central Scandes (Linderholm et al. 2014).

Extensive tree mortality and poor regeneration in high mountain forests and treeline ecotones during the Little Ice Age, contrasting with a period of higher-than-present treeline and summer temperature around 1000 years ago, is inferred from megafossil case studies in different parts of northern Fennoscandia and northwestern Russia (Kullman 1987, 2005; Selsing 1991; Shiyatov 1993, 2003; Karlén & Kuylentierna, 1996; Kremenetski et al. 2004; Hiller et al. 2001; Mazepa 2005; 2011; Kulti et al. 2006; Kharuk et al. 2013). Further support for the regional coherence of the view outlined above comes from dendroecological and multi-proxy studies carried out in the same region, including Greenland (Maasch et al. 2005; MacDonald et al. 2008; Shemesh et al. 2001; Grudd 2008; Lindholm et al. 2010; Vinter et al. 2010; Hanhijarvi et al. 2013; Rinne et al. 2014; Linderholm et al. 2014). Certain multi-proxy studies do recognize the Medieval Warm Period, but do not find it distinctly warmer than the past few decades (e.g. Moberg et al. 2005; Loehle 2007; Melvin et al. 2012; McCarrol et al. 2013; Briffa et al. 2013).

It may appear from Table 1 that treeline recession throughout the Little Ice Age was substantially larger in the northernmost part of the study

area than in more southerly regions. Aside of regionally somewhat different climate histories, this discrepancy may relate to a more snow rich climate in the north, which has specifically counteracted pine treeline expansion in this region (Kullman & Öberg 2009; Kullman 2010).

Positional treeline change is an indicator of a fundamental reorganization of the entire ecosystem (Fagre et al. 2003; Kullman 2007; Behringer 2010). Thus, higher-than-present treelines and temperatures for some centuries around AD 1000 could imply a generally biologically richer and more productive subalpine /alpine landscape at that time, which was gradually pauperized and structurally eroded during the Little Ice Age. The modest warming of the past century may have initiated a reversal of this process (Kullman 2010a, 2012), but the structure and composition of the Medieval biological landscape has not been fully re-established, as evidenced in widely different parts of the northern hemisphere (Payette 2007; MacDonald 2010; Kullman 2014).

In perspective of the late Holocene, there is nothing particularly unnatural, unprecedented or alarming about the modern warming and associated ecological change in high mountain Fennoscandia and adjacent northern regions (cf. Kobashi et al. 2011; Kullman 2013).

7 Conclusions

Radiocarbon-dated megafossil remains of Scots pine (*Pinus sylvestris* L.) were systematically searched for and recovered on the ground surface well above the present-day treeline along the entire Swedish Scandes. These findings reveal that the treeline was positioned as much as 115 m higher than today during the apogee of the Medieval period, about AD 1000-1200.

Since treeline positions and their dynamics are mainly constrained by temperature deficiency, the obtained elevational difference of 115 m implies that summer temperatures, for purely natural reasons, were about 0.7 °C higher than present during the

Medieval period. This inference is consistent with data from various parts of the northern hemisphere.

Climate warming over the past century has not yet been sufficient to restore the pine treeline to its Medieval level.

Given the obtained range of treeline change and inferred associated climate change over the past 1000 years, there is little to view the rate of extent of global warming as unnatural.

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Appendix I

Papers accounting for eye-witness reports of treeline recession and mountain forest decline during the final phase Little Ice Age in Fennoscandian mountain regions.

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