Finnish supra-long tree-ring chronology extended to 5634 BC

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Introduction

Remains of Scots pine stems are known to survive preserved over centuries and millennia as megafossils in the anaerobic conditions of peatbogs and bottom sediments of small lakes (e.g. Lundqvist 1959; Eronen 1979; Kullman 1980, 1999; Aas & Faarlund 1988; 1999). Each megafossil provides tree-ring series that represent the lifespan of an ancient tree that once lived in the palaeolandscape. Series bearing overlapping lifespans can be temporally synchronized by their common growth variability and averaged into mean chronologies that record the growth variability more reliably than any solitary series (Fritts 1976). During recent years, an increasing number of millennial tree-ring chronologies have been constructed in different parts of Fennoscandia. These are palaeoecological and palaeoclimatic records which are characteristically composed of both recent and subfossil pine tree rings (Eronen et al. 1999; 2002; Lindholm et al. 1999a; 1999b; Grudt et al. 2002; Gunnarson & Linderholm 2002; Helama et al. 2005a; Kirchhefer 2005; Linderholm & Gunnarson 2005).

In northernmost Finland, collection of megafossils was started by Eronen (1979) and culminated recently in the completion of a tree-ring chronology that continuously spanned back to 5520 BC (Eronen et al. 2002). Since then, this chronology has been utilized as a proxy for palaeotemperature (Helama et al. 2002; Ogurtsov et al. 2005) and it has provided information about former shifts of the forest limit and the tree limit (Helama et al. 2004b) and about stand density variations (Helama et al. 2004b; 2005b). Adjacent, in northernmost Sweden, a similar compilation of subfossil tree rings resulted in the completion of a continuous pine chronology spanning back to 5450 BC (Grudt et al. 2002). Considering the great number of sampling sites and sampled megafossils (Eronen et al. 1999; 2002; Grudt et al. 2002), the chronology construction seemed to have arrived at a critical point from which a further lengthening of the records would be hampered due to either differing geological, taphonomical or palaeoecological conditions prior to approximately 7.5 ka ago.

In the present paper we report on the lengthening of the Finnish supra-long tree-ring chronology using tree-ring samples predating any dendrochronological series from the region published to date. Dendrochronological crossdating of tree rings is described and the first attempt to unveil the palaeoclimatic conditions during the earliest years of the chronology is performed. We show that the elongation of the multimillennial chronology in Finland is possible and we discuss the factors that may influence further extension.

Materials and methods

Approaches prior to crossdating

Subfossil Scots pine (Pinus sylvestris L.) trunks were recovered from the bottom sediment of small lakes at the northern coniferous forest limit of Finnish Lapland (Eronen 1979; Eronen et al. 1999; 2002) (Fig. 1). Sample disks were cut with a saw on the shore and the megafossils were then returned to the lake. The ring-widths were measured from each disk along multiple radii to the nearest 0.01 mm.

Ring-width series of individual pines in the region are known to contain an age-related growth trend that typically follows the shape of a negative exponential curve (Lindholm 1996; Helama et al. 2005a; 2005b; 2005c). In addition, the ring-width series are autocorrelated (Lindholm 1996; Berninger et al. 2003; Helama et al. 2004c). Prior to dendrochronological crossdating and dendroclimatic interpretations, the ring-width time-series were detrended and pre-whitened accordingly.

Double-detrending was applied to the measured raw data. In the first detrending step, a modified negative exponential function (Fritts et al. 1969) or a linear trend (with negative or zero slope) was fitted to each ring-width series and the best fitting model was chosen as final model for the
individual series. Dimensionless tree-ring indices were then derived by dividing each observed tree-ring value by the value of the modelled curve or line (Fritts et al. 1969; Fritts 1976).

In the second detrending step, a 48-year spline function (Cook & Peters 1981) with 50% frequency cutoff was fitted individually to each tree-ring index series and, identically to the first detrending, the second index series was derived from the model as ratios. Utilization of such a flexible indexing curve was supposed to greatly reduce heteroscedasticity present in the initial ring-widths (Cook & Peters 1997; Helama et al. 2004c). The indices from the first detrending were expected to contain more long-period (i.e. low-frequency) variations than the indices from the second detrending, whereas the double-detrended indices were supposed to be more accurate concerning the high-frequency variations (Helama et al. 2004c). Consequently, the two sets of indices were used as follows: indices from the first detrending were used in dendroclimatic interpretations relating to the low-frequency growth variations, whereas the indices from the second detrending were entered into autoregressive modeling to be pre-whitened and further crossdated.

The structure of mathematical persistence in the time-series was determined using autoregressive models (for tree-ring applications, see Guiot 1986; Monserud 1986; Yamaguchi 1986; Monserud & Yamaguchi 1989). The order of the model was determined individually to each index series using Akaike’s (1974) Information Criteria. Residuals from these models were thus series that had practically lost their autocorrelation. This is particularly important for the detection of common growth signals and thus for cross-dating due to the well-known fact that autocorrelated series may show arbitrary synchronicity (Yule 1926; Bartlett 1935). Therefore, the pre-whitened index series were used to crossdate the tree-ring series.

Fig. 1. The study area, with the sampling sites. Vertical and horizontal axes are labelled with the national coordinates (see Eronen et al. 1999; 2002).

Approaches to crossdating

Series of tree rings exhibit distinct growth variability that is not unique to each tree but common among the contemporary samples due to external factors that control growth; in Finnish Lapland this is largely mid-summer temperature variability (Hari & Siren 1972, Lindholm 1996; Helama et al. 2004a). Crossdating uses this synchrony to temporally match the series by their common growth signal (Douglass 1941; Fritts 1976; Holmes 1983; Orton 1983; Munro 1984; Wigley et al. 1987; Yamaguchi 1991), and each ring in the series can be related to actual and absolute calendar years (AD or BC).

Agreement between the undated series and the reference (master) chronology can be quantified statistically e.g. by the Pearson correlation between the two series \( R_{\text{master}} \) (Holmes 1983). Since the significance of the obtained correlation depends on the sample size (number of years common to both series), Baillie & Pilcher (1973) introduced the \( t \)-statistic:

\[
t = \frac{R_{\text{master}} \sqrt{(N - 2)}}{\sqrt{1 - R_{\text{master}}^2}}
\]

where \( N \) is the number of years common to the sample and master series.

Given the series of unknown dates are compared to the reference chronology multiple times, one would expect to obtain spuriously significant correlations by chance (Orton 1983; Munro 1984; Wigley et al. 1987). In order to allow for multiplicity, Wigley et al. (1987) suggested calculating a modified probability that accounts for the multitude of dating trials. In any single trial with \( p \) as the probability of a dating success, the appropriate significance level \( P \) in the presence of multiplicity \( M \) was determined by Wigley et al. (1987) as:

\[
P = 1 - (1 - p)^M
\]

According to Wigley et al. (1987), the unbiased crossdating is judged in three steps, by first calculating the correlation coefficient, then determining an associated significant level \( p \) through \( t \)-value and finally adjusting the obtained significant level for multiplicity by obtaining the appropriate significance level \( P \). The unbiased derivation of \( P \) is guaranteed if all crossdating trials are independent (Wigley et al. 1987). Pre-whitening prior to crossdating (see above) is expected to largely secure the issue of serial independency (Monserud 1986; Yamaguchi 1986). Although highly numerical, the process of crossdating was, however, not solely based on statistical criteria, but accompanied with visual comparison of the plotted series along the process.

The mean chronology was achieved by averaging the full set of crossdated tree-ring series. In this study, we did not aim to adjust the variance of the mean chronology due to potential influence from the temporal variations in the sample size (e.g. Shiyatov et al. 1990; Osborn et al. 1997).
Supra-long tree-ring chronology

Construction of the chronology along the altitudinal, latitudinal and longitudinal gradients has been described by Eronen et al. (1999; 2002) and Helama et al. (2004b). Eronen et al. (1999) reported the collection of 1722 megafossils (1450 of which were dated) from 43 lakes. Four of the sites are located in Norway, close to the Finnish border. Eronen et al. (2002) reported additional sampling of 1436 megafossils from 35 lakes, so the hitherto existing complete collection includes 3158 megafossils. In this paper, the subfossil data set referred to contains an additional tree-ring series from 1031 megafossils and 258 living trees, and spans continuously from the present time back to 5520 BC, as previously reported by Eronen et al. (2002). Selection of the samples to the stripped chronology was based on the data quality control by $R_{\text{master}}$.

Oldest samples

Reworking previously collected but as yet undated megafossils and their tree-ring series led to successful crossdating of additional dendrochronological material to the established supra-long chronology (Eronen et al. 2002). A group of tree-ring series with unexpectedly old geological ages was discovered during re-examination of the data. Based on the aforementioned criteria, the crossdating of the samples is described in the following.

Results

A total of 12 tree-ring series was successfully crossdated against the established master chronology (Fig. 2A). Agreement between the newly crossdated segment and the established master is shown in the example presented in Fig. 2B. The series bear their geologically oldest (ontogenetically youngest) rings between the years 5634 BC and 5520 BC and their geologically oldest (ontogenetically oldest) rings between the years 5457 BC and 5257 BC. The length of the new segment is thus 379 years, with maximal sample replication (12 series) between the years 5457 BC and 5520 BC. Temporal overlap between the new segment and the master chronology is 264 years. The probability of obtaining depicted agreement by chance, accounting for multiplicity in the context of supra-long chronology (Eq. 2), is very small (Fig. 2B). Lengthening of the master chronology back to 5634 BC is thus achieved (Fig. 2A). In its present form, the chronology is the longest conifer tree-ring chronology in Eurasia.

The oldest megafossils originated from five lakes: Lake Eteläinen Haukijärvi and Lake Hattulompolo in north-west Finnish Lapland, and Lake Selkäjärvi, Lake Annanjärvi and Lake Vuotkimlompolo in north-east Finnish Lapland. It is, however, notable that six out of seven megafossils bearing pith years prior to 5550 BC originate from the north-east.

The newly added tree-ring chronology displays variations at different time-scales (Fig. 3A). Besides interannual variations, several long-term changes are evident throughout the record. The chronology is punctuated by negative growth anomalies at multi-decadal time-scales (Fig. 3B). The severest negative growth anomaly occurred at the very start of the record. However, the overlapping confidence limits indicate that the coolness of this very early period was not that anomalous compared to any other detected negative growth period (Fig. 3B).

Discussion and conclusions

Extended chronology

We have presented a new contribution to the Finnish supra-long tree-ring chronology (Fig. 2). Importantly, pre-whitening of the individual ring-width series prior to crossdating was applied to secure the issue of serial independency in the ring-widths (Monserud 1986; Yamaguchi 1986), thus allowing unbiased crossdating. In addition to lengthening the pre-existing master chronology, the new contribution also increases the chronology sample size (Fig. 2A) and thus enhances the estimation of the master chronology. This, in turn, will help to crossdate further megafossil samples of contemporary or even older geological age that might be found in the future.

Indicators of past climates

In northernmost Finland, tree-ring widths of living Scots pine correlate significantly and positively with mid-summer temperatures, with especially high correlations to July temperatures (Mikola 1950; Siren 1961; Lindholm 1996; Nojd & Hari 2001; Macias et al. 2004). As previously shown, also ring-width series from megafossils correlate significantly with observations of July mean temperatures from the 18th and 19th centuries (Helama et al. 2004a). Typically, Pearson correlation coefficients between 0.45 and 0.65 are found, depending on the subset of data (e.g. Helama et al. 2004a). The regional ring-width chronologies have accordingly been used to reconstruct the mid-summer temperature variability (Lindholm 1996; Lindholm & Eronen 2000; Helama et al. 2002). Although the ring-width variations of the final chronology were not transferred to reconstructed temperature variations in this study, the obtained growth anomalies can be interpreted accordingly, as indicated by the aforementioned growth-climate-correlation. In so doing, the periods with high tree-ring indices could be expected to coincide with the periods with warm summer conditions, and vice versa. Since also the pine regeneration is significantly influenced by growing season temperatures via the frequency of seed-years (Siren 1961; 1993a; 1993b; Henttonen et al. 1986), it can be assumed that prolonged past positive growth phases have predominantly occurred in association with enhanced pine regeneration in the region (Siren 1961; 1993a; Kullman 1996).

Palaeoclimatic inferences

The amount of fossils preserved since any given period of time is controlled by natural fluctuations in the ancient
communities and taphonomic processes (Wilson 1988; Martin 1999). Previous studies have suggested that the main factor influencing the sample size variations of the present chronology was the naturally fluctuating stand density at the former forest limit (Helama et al. 2004b; 2005b). Local preservation conditions are a second factor influencing sample size (Helama et al. 2004b; 2005b). For example, the interval between 800 BC and AD 100 shows a notable decrease in the megafossil sample size in Finnish Lapland, with a drastic culmination around 500 BC (Eronen et al. 1999; 2002; Helama et al. 2004b). Independent evidence from megafossil tree-ring series have shown that the same period may have experienced intensified forest-limit stand thinning (Helama et al. 2005b). Since pine regeneration is largely controlled by changes in growing season temperatures, it seems likely that the aforementioned deficit in megafossils between 800 and 200 BC was mainly due to prolonged cool climatic conditions. Supporting evidence comes from a notable thermohaline circulation reduction in the North Atlantic deep-water formation (Bianchi & McCave 1999; Bond et al. 2001). Via atmospheric couplings, this could have implied concomitant summer cooling in the study region (Helama et al., unpublished data). However, apart from the forest-tundra ecotone, a higher number of megafossils dating back to the first millennium BC have been unearthed from more southern areas in Finnish Lapland (Eronen et al. 2002).

The natural fluctuations during the first millennium BC may actually be seen parallel to conditions that may be analogous to the first years of the chronology. Also the times around 8.4 to 8.0 ka ago were known to have experienced notable changes in the thermohaline circulation (Alley et al. 1997) that have seemingly caused considerable climatic cooling, especially around the North Atlantic sector.
regeneration (Fig. 3B). Since the reduced reproduction in ancient communities would have led to extremely poor fossil assemblages, it would be tempting to link this early deteriorated phase to the aforementioned natural reasons that to date may have prevented the temporal extension of Finnish (Eronen et al. 2002) and Swedish (Grudd et al. 2002) tree-ring chronologies. However, compared to the multi-centennial lifespan of northern pines (Leikola 1969), the duration of five decades (Fig. 3B) would not be sufficient to explain a possible forest limit retreat prior to around 5600 BC. Consequently, this early cool period is not long and severe enough to explain the decreasing number of megafossils over the very early years of the chronology. Only further lengthening of the chronology may help to quantify former temperature variations and their concurrent influences to forest-limit pine populations during this period.

Potential for further chronological extension

We have succeeded in extending the pre-existing chronology by reworking stored fossil material. Further lengthening of the chronology would likely require fieldwork at new sampling sites. The regional pollen influx data show that pines probably first appeared in the region prior to first years of the Finnish supra-long tree-ring chronology (e.g. Hyvärinen 1975; Seppä & Weckström 1999), indicating potential for older megafossil findings. Accordingly, radiocarbon-dated pine megafossils older than the presently available material were discovered in northernmost Sweden (Kullman 1999). As hypothesized previously, the early Holocene discrepancy between the pollen and megafossil evidence may imply a delay of the post-glacial pine forest establishment in the region until about the Mid-Holocene (Helama et al. 2004b).

Geologically, the oldest megafossil samples predominantly originate from north-east Finnish Lapland, indicating an increased likelihood of finding even older megafossils there. Given that the further lengthening of the master chronology has so far been prevented by delayed pine forest immigration and by a multi-centennial climatic deterioration around 8 ka ago, older material might be found in more southern localities, in analogy with the climatic deterioration between 800 BC and AD 100. Such localities are expected to lie above the highest postglacial shoreline (Eronen & Haila 1990).

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