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Dendroclimatology in Fennoscandia – from past accomplishments to future potentials

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Abstract

Dendroclimatology, i.e. using tree-ring data to reconstruct past climates, in Fennoscandia has a strong tradition. Due to the high-latitude location of the region, trees are sensitive to climate; in general to temperatures during summer. However, a strong gradient from the oceanic west to the continental east, makes it possible to find trees that respond to other parameters, such as precipitation and drought. Situated in a sparsely populated part of the Boreal belt, Fennoscandia with its large areas of old-growth forests is suitable for constructing tree-ring chronologies reaching far back in time. Indeed, some of the world longest tree-ring chronologies are found in the region, covering all, or most of, the Holocene. In addition to providing valuable information about regional climate variability during the Holocene, tree-ring data have played significant roles in recent reconstructions of hemispheric and global temperatures as well as large-scale circulation patterns. Here we review the field of dendroclimatology in Fennoscandia, showing the wealth of climate information obtained from various tree-ring parameters (ring widths, density and stable isotopes), and look in to future possibilities.

1 Introduction

In order to better understand climate change both from a natural and anthropogenic induced origin, analyzing the historical climate and its behaviour can give indications of what to expect in the future (Bradley, 1985). Instrumental measurements of temperature and other climate variables have been done with mixed quality since the 18th century but a century later the set of observing sites attained sufficient geographical coverage to calculate a global average (Jones and Moberg, 2003). Obviously this short time period is not enough to understand past climate variability, and other climate indicators need to be utilized (e.g., Mann et al., 1999). High-resolution reconstructions of past climate are mainly based on corals, tree rings, sediments and ice cores. These reconstructions are calibrated against instrumental records, but the reliability of a reconstruction may also be inferred from comparisons with modelling results from runs of coupled atmosphere-ocean circulation models (Collins et al., 2002). Analyses of long proxy records can emphasize distinctions between natural long-term modes and anthropogenic induced climate variability. Presently, a large number of hemispheric and global temperature reconstructions are available (see Mann, 2002). However, these do not provide information about regional-scale variations, where regions with key climatic features may be masked in hemispheric or global reconstructions (Luterbacher et al., 2004). Consequently, studies of regional climate variability are very important when impacts of climate change on the environment are evaluated (Shindell et al., 1999).

Reconstructions of Holocene climate variability in Scandinavia have mainly been based on relatively low-resolution climate proxies such as: fluctuations of glaciers (e.g., Karlén, 1976), tree-limit variations (e.g., Kullman, 1995), pollen/macrofossil analysis (e.g., Barnekow, 2000), speleothems (e.g., Lauritzen and Lundberg, 1999), peat humification (e.g., Nilssen and Vorren, 1991), and lake sediments (e.g., Yu and Harrison, 1995). However, if records with yearly resolution are required, the most suitable method available is to examine tree-rings (Gouirand et al., 2008).

This review will focus on dendroclimatology, the study of the relationships between climate and tree-growth parameters and their use in the reconstruction of past climates, in Fennoscandia. Fennoscandia, constituting of Norway, Sweden and Finland, is a region where remote virgin forests are common, and is thus highly suitable for dendrochronological studies. This paper will begin with a brief summary of the dendroclimatological achievements in the twentieth century, before the science “came into fashion”. Then, recent accomplishments will be described in more detail. We finish with an outlook of future prospects in the field of Dendroclimatology in Fennoscandia: what more can we do?

2 Dendroclimatology

In extra tropical tree species which are exposed to seasonal variations, defined annual growth bands, tree rings, are produced. Different features of these tree rings can reveal details about in what conditions or climate they were formed (Schweingruber, 1987). The annual growth of trees represents a combined record of different environmental forcing factors, one of which is climate (Briffa et al., 1998a). Factors that have large impact on tree growth are temperature, soil-moisture, and availability of nutrients etc. (Raven, 1999). When temperature is explored, the sampling sites of the trees need to fulfil certain criteria that eliminate or marginalise the effect of other variables that usually affect them. Typically, these locations are found near the altitudinal or latitudinal limits of a certain species (Cook and Kairiukstis, 1989). However, non-climatic factors such as stand-competition or silvicultural intervention can influence tree growth, so in order to obtain an optimized climate signal from the trees, the selection of sampling-site is crucial. Carefully chosen trees can thus be used as proxies for local-to-regional dominating climate features. Furthermore, tree growth is a function of multiple influences, and e.g. Linderholm and Chen (2005) have found that it is also possible to extract information of less dominant climate features that may affect growth even outside the vegetation period.

Tree rings have played an important role in establishing how climate has varied in the recent past (Jones et al., 2009). The strength of tree-ring records is the annual resolution and the spatial extent of climatically sensitive chronologies. Today there exist vast networks of tree-ring chronologies at mid-to-high latitudes, and these networks have been utilized to reconstruct spatiotemporal climate variability, mainly temperature, in the last centuries to millennia.

2.1 Tree-ring parameters

When analyzing tree-rings, a variety of parameters are studied. The most commonly used parameter is radial measurements of tree-ring widths, followed by density measurements of the radial cell growth and chemical analysis of stable isotopes. For the benefit of the reader, short descriptions of annual ring formation and the different tree-ring parameters are given in the following paragraphs (for a more in-depth description we refer to Fritts, 1976, and references there).

2.1.1 The annual growth ring

The growth of woody plants can be divided into primary and secondary growth. The primary growth in a plant occurs in the apical meristem and forms primary tissues, and the primary growth involves shoots, leaves and root and is mainly lengthwise. The secondary growth takes place in the cork and vascular cambium inside the bark. Here secondary phloem (outwards) and xylem (inwards towards the pith) are formed and produce radial growth of the stem. The cells formed on the outside of the cambium become phloem which conducts the nutrients of the tree, and the cells formed on the inside of the cambium become xylem and conducts water and minerals. The xylem is also the woody tissue in the tree. The xylem consists of tracheids, parenchyma and resin ducts in conifers. The tracheids are vertically oriented elongated cells with lignified wall which transport water and mineral salts. These cells grow in different rate throughout the growing season with large and thin-walled cells in the early spring, called early wood. Gradually smaller and more thick-walled cells are formed towards the end of the growing season called late wood. Before the winter, radial growth abruptly ends and the tree enters the dormant period where little or no growth occurs. Together the lighter early wood and the darker late wood form an annual growth ring. When the growth is resumed in the spring large cells are formed again creating a stark contrast between late wood and early wood resulting in a clearly visible annual ring (Raven, 1999).

2.1.2 Tree-ring widths

From living trees cores, 5 mm in diameter, are usually extracted at a height of ~1.3 m from the base of the trunk using an increment borer. When dead wood is concerned, a disc from the tree is usually taken, if possible at the same stem height. Annual tree-ring widths of each sample are then measured, usually with a precision of 1/100 mm, and visual inspection as and basic statistics are used to cross date all samples in order to assign to each ring the correct calendar year. A tree-ring series can be expressed as a linear composition of several sub-series (e.g., Cook, 1990). These sub-series include an age-related growth trend, a climatic signal common to all trees at the site, influence of endogenous (single tree) and exogenous (common to most trees) disturbances in the stand. In order to remove the non-climatic growth-trend caused by changing age and geometry of the tree, all individual tree-ring width series are standardised by fitting an approximate growth-function to it, e.g. a negative exponential curve or a straight line etc. (Fritts, 1976). The tree-ring series are then divided by the fitted curve, and the resulting so called indices are all centred around 1 and can thus be averaged to produce the standardised chronology. The method of standardization significantly affects which frequencies of variability can be recovered from the tree-ring data. Presently, Regional Curve Standardization (Briffa et al., 1992) is the most widely used method to preserve low-frequency (>100 years) information. Although the standardization issue is far from settled, it will not be further explored in this paper.

2.1.3 Density

While measuring ring width variations is the most common and least complicated approach in dendroclimatology, an increasing number of works utilizes density variations in the annual rings. Densitometric analysis of wood-tissue is an integrated measurement of all the components of the annual rings, e.g. thickness of cell walls, proportion of fibres etc. (Polge, 1970). Since the early and late wood differ in characteristics (see above), the detailed distinction of cell-density can be quantified. Thin slices of increment cores are exposed to narrow and high energy X-ray beams at short intervals (∼20 μm) and a high-resolution digital image is produced. The radiographic images are then evaluated with an image analysis system, e.g. WINDENDRO (Guay, 1992), which provides several parameters: maximum and minimum density and the mean densities of the early wood, late wood and of the whole ring.

One advantage with density variations, compared to ring-widths, is the much weaker age trend, demonstrated by Grudd (e.g., 2008), which suggests that standardization of density values potentially recover more low frequency variability. Maximum density is most frequently used in dendroclimatology, and this parameter has been shown to be highly correlated to warm-season (April–September) temperatures in high altitude and latitude areas (e.g., Briffa et al., 1988a, 2002b; Schweingruber et al., 1993). Since tree-ring widths may incorporate information from before the actual growing season (Fritts, 1976) as well as having a shorter optimum seasonal signal (Briffa et al., 2002b), density data is to be preferred when reconstructing warm season temperatures.

2.1.4 Stable isotopes

Stable isotopes (mainly δ^{18}O and δ^{13}C and δD) from tree-ring species, such as cellulose, can provide information of temperature, precipitation, humidity and soil moisture depending on the growth environment of the trees (Burk and Stuiver, 1981; McCarroll and Loader, 2004). Also it is likely that the annual variations in isotope ratios in tree rings are lacking long-term (>50 years) age related trends, and thus will reflect climate variations on century time scales. One additional advantage with assembling a number of annually resolved isotope chronologies is that they are comparable to and can be used to calibrate isotope series from other climate proxies, such as ice cores, speleothems and lake sediments.

3 Early Fennoscandian dendroclimatological studies

The link between the annual growth of trees and climate has under a long time been the subject of scientific investigations. Already in the 18th century, the annual growth of trees was related to favorable summer conditions (Carl Fredric Broocman, 1709–1761) or winter severity (Carl von Linné, 1707–1778). Finnish Ulric Rudenschöld (1704–1765) compared pine trees in Northern and Southern Finland trees finding both differences and similarities, where he accounted the similarities to regional climate-conditions and the differences to both climate and soil-conditions. The Danish statesman Christian Ditlev Reventlow (1748–1827) made tree-ring investigations on oaks and beeches in the early 19th century, not only sampling the base of the tree but also at different heights of the stem. Dendroclimatology thus has strong traditions in the Nordic countries, but it was the American astronomer Andrew Ellicott Douglass (1867–1962), who in the beginning of the 20th century established a statistically valid relationship between climate and tree-ring widths (Douglass, 1909, 1914). He set out to investigate the influence of sunspots on precipitation in America and chose tree-rings as a suitable drought indicator. During his studies he noted that tree-rings growing in similar environments showed homogenous growth patterns, despite the sites being far apart. He also made investigations of European data, e.g. from southern Sweden and Norway were sunspots was the focal point (Douglass, 1919). Douglass' sunspot-curve was found to be in good agreement with these localities except for the inner coast of Norway, where the agreement practically was inverted.

In some key investigations during the early decades of the 20th century, most of the features of modern Fennoscandian dendroclimatology were outlined. In a thorough investigation, Erlandsson (1936) established the strong dependence of Scots pine (*Pinus Sylvestris* L.) to summer temperatures in the northern region of Fennoscandia, which had also previously been noted by the Norwegian Eide (1926). Erlandsson noted that July temperatures specifically were well correlated with tree-ring widths and that precipitation regardless of when it occurred had a weak, if existent, relationship with tree growth. Erlandsson also developed a predecessor of the Regional Standardization Curve (RCS) method, later improved by Briffa et al. (1992). The growth-trends of the trees from each locality included in Erlandsson's study were "Summed up from a common starting-point (the inner-most ring) independent of the chronological age...", and an average of each annual ring was calculated resulting in a mean growth-trend. The mean growth-trend was then used to standardize every tree-ring series.

Other important works in the development of a Fennoscandian network of tree-ring chronologies were made in Norway in the mid 20th century, where tree-ring chronologies from both Scots pine and Norway spruce (*Picea Abies* L. *Karst*) were constructed. Eidem (1953) found that the chronologies from sites in the interior of Norway as well as from the coastline showed considerable differences, and that Norway spruce correlated better with June but Scots pines with July temperatures. The difference between pine and spruce was also manifested by the pronounced autocorrelation in pine, which seem to be absent in spruce, where the difference depends on the different development and assimilation-rates in the needles of pine and spruce (Ording, 1941). Jonsson (1969) however, argued that pines showed stronger autocorrelation than spruce. Removing the autocorrelation from the direct or indirect influence of climate in pine- or spruce chronologies is however not without problems as low-frequent variations might also be removed (Hustisch and Elfving, 1944).

Schove (1954) stated that tree-ring analysis involves three initial limitations: "only one species should be considered at the time, the trees should be from a small climatically uniform region and the growth measurements for each year should be corrected for age and standardized by a single objective method". Furthermore, when deriving climatic evidence from such a diverse region as Fennoscandia, more than one species of tree is needed, these trees should be sampled from a large area and different methods of standardization should be used to investigate the sensitivity of the data to correction methods.

4 Spatial variability of tree growth/climate relationships in Fennoscandia

Despite the high-latitude setting of Fennoscandia, the proximity to the North Atlantic Ocean in the western part of the region results in a gradient from oceanic climate in the west to continental in the east. Also, Fennoscandia spans over several degrees of latitude, which means large differences in seasonal climate, e.g. the length of the growing season which is of importance for tree growth. Thus, it is not expected that trees will respond similarly to climate across the region. Mäkinen (2002), investigating growth/climate relationship of Norway spruce across latitudinal and altitudinal gradients in Central and Northern Europe, noted that the temperature influence on tree-growth increased with altitude and latitude, while the opposite was found for precipitation. Helama et al. (2005) examined four tree-ring width chronologies in a north-south transect in Finland and found evidence of an eco-geographical gradient where the northern chronologies showed the typical mid-summer temperature response and all chronologies had positive correlation with early-summer precipitation but more so in the south. The low-frequency variability common to all chronologies was related to the North Atlantic Oscillation (NAO), and a weakening of common high-frequency variability from north to south was accounted to increased growth-competition (Helama et al., 2005). Andreassen et al. (2006), studying Norway spruce in Norway, found that summer temperature was the limiting factor for tree growth at northern and high altitudes sites, but in the southeastern lowlands summer precipitation was growth limiting. Andreassen et al. (2006) also found that below a threshold of June temperatures of 12–13°C, spruce was expected to be sensitive to temperature and above it to precipitation. Analysing 21 Scots pine chronologies along a westeast gradient in northernmost Fennoscandia, Macias et al. (2004) found a common climate signal (July temperatures and May precipitation) across the Scandinavian Mountains. Still, differences between coastal and more continental sites were observed, and this difference increased from the late 1800s/early 1900s to the late 1900s, suggesting a differentiation in regional climate occurring in the twentieth century. In a study of nine Scots pine tree-ring width chronologies along a gradient at 62–64° N in central Fennoscandia, Linderholm et al. (2003) noticed higher growth variability and stronger response to climate in the oceanic area west of the Scandinavian Mountains, compared to the more continental areas further east. Moreover, Pine growth responded positively to summer temperatures in the western areas, and positively to summer precipitation in the east.

5 Climate reconstructions

5.1 Temperature

Although the strong relationship between conifer growth and summer temperatures at the latitudinal tree-line in Northern Fennoscandia had previously been established, (e.g., Erlandsson, 1936; Schove, 1954; Sirén, 1961; Jonsson, 1969; Bartholin and Karlén, 1983), the first reconstruction of summer temperatures using tree-ring data was made in the 1980s. Still, already in the 1960s, Sirén claimed that his chronologies would suffice directly as summer temperature records (Sirén, 1961). Aniol and Eckstein (1984) used chronologies from 4 locations around Torneträsk, sampled and described by Bartholin and Karlén (1983), to reconstruct July temperatures from 1680–1983. It is not clear if they use the calibration-verification methods described by Fritts (1976) but they claim a correlation coefficient of 0.58 for the period 1880–1979. The Bartholin and Karlén (1983) chronology went back to AD 436 but Aniol and Eckstein (1984) hesitated to reconstruct July temperatures this far because of "...the striking deviations from average temperatures around 1750–1830" (Aniol and Eckstein, 1984). A more transparent reconstruction of summer temperatures (July–August) back to AD 1700 was made by Briffa et al. (1988b). They used a network of tree-ring width chronologies from Northern Fennoscandia and a few density chronologies from Northern Sweden and reduced them to principal component predictors. Over the calibration-verification periods 1852–1925 and 1926–1964, the tree-ring data explained 69 and 32% of the variance respectively in observed temperatures. Briffa et al. (1988b) concluded to re-

mark that although the year-to-year variability was reproduced with fidelity, the long timescale fluctuations above 50 years could not be reconstructed because of limitations in the standardization technique.

The summer temperature reconstruction was further developed by Briffa et al. (1990), extending the reconstructed period to April–August, using tree-ring data from Torneträsk. The reconstructed period spanned AD 500–1975 where tree-ring widths and density together explained 51% of the variance in observed temperatures over the 1876–1975 calibration period. Based on the reconstruction, Briffa et al. (1990) found no evidence of a homogenous Medieval Warm Epoch, and a short Little Ice Age was interpreted to have occurred around 1570–1650. However, the weaknesses in the standardization method made it difficult to retrieve centennial to multi-centennial variation in the reconstruction, why the claim of a short Little Ice Age could have been a bit premature. An effort to enhance the low-frequency variation was made by Briffa et al. (1992), where a "new" standardization method was applied to the same dataset used Briffa et al. (1990), although with some additional tree-ring width series. Instead of standardizing every tree-ring series individually all series were arranged starting at their cambial age, and every year was averaged into a grand mean curve of the whole population. This method was called Regional Curve Standardization (RCS), and was developed from the method used by Erlandsson (1936) (see above). A consequence of using the RCS method was a lowered common signal among the trees, but the low-frequency variability was greatly enhanced and a longer more pronounced Little Ice age emerged around 1570–1750.

Up to now, most efforts in building tree-ring chronologies and making climate reconstructions had mainly been restricted to northern Fennoscandia. However, Kalela-Brundin (1999) expanded the network of reconstructions in Fennoscandia by investigating climate from a Scots pine tree-ring series sampled in Femundsmarka, in the eastern part of central Norway. In addition to whole tree-ring widths, Kalela-Brundin (1999) measured the width of early wood and late wood separately and made a reconstruction of July and July–August temperatures 1500–1985, based on combinations of these parameters. The reconstructions explained 52 and 49% of the variance in observed July and July–August temperatures for the period 1872–1993, respectively.

Another effort to expand the diversity of locations in Fennoscandia was made by Kirchhefer (2001), who investigated Scots pine tree-ring widths from three coastal sites in Northern Norway; Vikran (northernmost), Stonglandseidet and Forfjordsdalen (southernmost). Due to the dramatic landscape in the area, differences in tree responses to climate were evident, where tree-growth at Vikran was associated with a shorter growing period than at the two more southern sites. Based on these chronologies, a set of July–August temperature reconstructions were made, where the longest, based on data from Forfjordsdalen, spanned 1358–1989.

In a new approach to develop a summer temperature reconstruction for the whole of Fennoscandia, Gouirand et al. (2008) selected, from a network of tree-ring width and density chronologies, those having the strongest temperature information a priori, to obtain a strong common climate signal suitable for a regional-scale reconstruction. Depending on the number of tree-ring chronologies available through time, seven separate reconstructions were created. They showed that it was possible to get a good spatial representation of the reconstructions back to around AD 1700, with correlations of >0.7 with observed summer temperatures for nearly the whole of Fennoscandia, and even higher correlations (>0.85) over much of central-northern Fennoscandia. One important conclusion was that relatively few (12) chronologies could represent Fennoscandian summer temperatures equally well as a large number (30) of chronologies. Furthermore, it was stated that in order to extend a spatially strong reconstruction back in time (and to update it to the present), only a few key sites are needed. Thus, rather than sampling a large number of new sites, work should be focuses on improving existing sites included in the reconstruction as well as finding a few more key sites.

5.2 Precipitation

Reconstructions of precipitation in Fennoscandia are sparse, but some efforts have been done to extract information about rainfall. Due to the high latitude and the proxim-

ity to the North Atlantic Ocean, trees do not in general show such strong precipitation signals that may be found in more continental regions or at the mid-latitudes. Moreover, dendroclimatological reconstructions of precipitation are further complicated by the high local variability (compared to temperature) and the fact that most precipitation during summer falls as convective precipitation, so that large amounts of precipitation may fall in very short times. Thus, the importance of selecting a suitable site is highly important when seeking precipitation information from Fennoscandian tree-ring data. The precipitation signal in tree-ring data is usually secondary to the temperature forcing, especially in the west-central and northern parts of Fennoscandia (Linderholm et al., 2003; Macias et al., 2004). The strongest association between precipitation and tree growth is generally found in summer, where it, in general, is positive in southern and eastern Fennoscandia and negative in the northern and western parts, (Lindholm et al., 1997; Linderholm et al., 2002, 2004; Seftigen et al., 2009a), although positive responses to May precipitation were found in northernmost Fennoscandia (Macias et al., 2004). In the central Scandinavian mountains, late winter/early spring precipitation was found to have a significant influence on tree-ring widths from Scots pines growing ca 200 m below the tree-line (Linderholm, 2001).

Due to this lack of strong and consistent precipitation signals in Fennoscandian conifer tree-ring data, few attempts have been made to reconstruct this parameter. Nevertheless, Helama and Lindholm (2003) reconstructed annual variability of rainfall and drought in southeastern Finland. May–June precipitation explained 36 and 19% of the variance in the tree-rings over the calibration/verification periods 1918–1951 and 1952–1985 respectively, and although these statistics are not entirely satisfactory, a reconstruction of summertime rainfall back to AD 874 was made. Reconstructed dry periods occurred in the 12th, 14th and 17th centuries and wet spells occurred in the 11th, 15th and 18th centuries. Scots pine tree-ring widths data from east-central Sweden was used to reconstruct the Standardised Precipitation Index (SPI), which is a drought indicator, back to 1750 (Linderholm and Molin, 2005). Results were similar to the Finnish study, where around 25% of the variance in the observed SPI data could be obtained using tree-ring data. The most pronounced dry period was found in the beginning of the 19th century, between 1810 and 1835, and this was corroborated by evidence from a farmer's diary. An attempt to reconstruct the regional precipitation pattern back to 1735 for the region was also made by Seftigen et al. (2009a). Based on 5 Scots pine chronologies the model explained 43 and 24% of the variance in the precipitation over the calibration/verification periods (Fig. 2). Using the same tree species, Linderholm and Chen (2005) developed a 400-year long winter (September–April) precipitation reconstruction for the west-central Scandinavia. Over the period of 1500–1990, winter precipitation in central Scandinavia showed an increasing trend during 20th century (within the frame of 400 years). This centurial variability was imposed over variability at shorter frequencies, expressed as periods of negative precipitation anomalies occurred in early 1500s, 1590s, 1620s, 1710s, 1870s, 1900s, and around 1920s. Several of these periods were also present in the reconstruction of Helama and Lindholm (2003) (early 1500s, 1900s, 1920s), however, overall comparison of two reconstructions over the common period shows large differences between reconstructions, sources of which can be both local differences in precipitation dynamics as well as site-specific effects.

In the southern parts of Fennoscandia, pedunculate oak (*Quercus robur* L.) is another tree species which could potentially be promising for precipitation reconstructions. Oak growth is strongly influenced by early growing season precipitation and the spatial pattern of growth anomalies have been shown to follow spatial pattern of major regional weather anomalies (Drobyshev et al., 2008). Multi-century oak chronologies developed in this region (Bartholin, 1975) may therefore prove to be a useful proxy for historical growing season precipitation. Currently, existing and recently developed oak chronologies are analyzed within the frame of an ongoing project aimed at the reconstruction of precipitation dynamics in southern Fennoscandia over the last 500 years (see www.ekskog.org/proxy500).

6 Multi millennial temperature reconstructions

As described earlier, tree-ring records play a prominent role in attempts to establish how climate has varied in the past. In Fennoscandia hundreds of tree-ring chronologies exist, of which some have been utilized for climate reconstructions. However to further utilize large-scale average and spatial pattern of climate variability on millennial timescales, a dense network of tree ring reconstructions is needed (e.g., Jones et al., 2009). Globally, only few tree-ring chronologies extend back over the past 1000 years (Jansen et al., 2007). One main challenge in constructing millennial-long chronologies is to find trees that covers such a long period of time, either living or dead trees that have been preserved through time. No living trees exceeding 1000 years can be found in Fennoscandia. In order to develop "supra long" tree-ring chronologies, data from living, recently dead and preserved wood from protective environments such as peat bogs or river and lake sediments, so called subfossil wood, is needed, and potential sites with known subfossil material are limited (Jones et al., 2009). Although the number of available >millennial long tree-ring chronologies is increasing, it still remains small and the efforts of developing these are fully justified. Northern Scandinavia has been shown to be suitable for developing long tree-ring chronologies, because of its richness of natural forests with of old living trees, dead trees (snags) which may resist decomposition for centuries, and subfossil trunks and stumps found in small mountain lakes and peat bogs. Presently three multi-millennial tree-ring width chronologies exist, spanning more than 6000 years, which will be described below (Fig. 1).

6.1 Torneträsk

The area is located in the northernmost part of Sweden, where the Scandinavian mountain range acts as a barrier to warm and moist air masses from the Norwegian Sea and consequently forms a strong east-west climate gradient in precipitation and seasonal temperature variability. The Scots pine material consists of living trees, dry dead trees (snags) preserved on land and subfossil wood preserved in lakes and lake sediments. As mentioned above, extensive sampling in the area occurred in 1970s and 1980s (Bartholin and Karlén, 1983; Bartholin, 1984) and the data was later used to make a reconstruction of summer temperature spanning AD 540–1980 (Briffa et al., 1990, 1992). In the mid 1990s, the Torneträsk chronology was updated and extended within the ADVANCE-10K project (Briffa et al., 2002a) to cover the last 7400 years (Grudd et al., 2002). The Torneträsk chronology is one of the most well known multi-millennial tree-ring chronologies, and has been extensively used in large-scale climate reconstruction (Jones et al., 1998; D'Arrigo et al., 1999; Mann et al., 1999; Briffa et al., 2002b; Moberg et al., 2005). A selection of the material collected by Bartholin was used to produce a maximum density chronology covering AD 443–1980 (Schweingruber et al., 1988). This density chronology has recently been updated by Grudd (2008) within the Millennium project, so that it now covers the period AD 500–2004, and is presently one of the longest density records in the world. The updated MXD chronology show generally higher temperature estimates than previously reconstructed from the region and also that the late-twentieth century is not exceptionally warm in a 1500-year context. Moreover, Grudd (2008) argues that the "Medieval Warm Period" in northern Fennoscandia was warmer than previously predicted.

6.2 Jämtland

In the late 1990s, the province of Jämtland, Sweden, was selected as a suitable location for building a multi-millennial tree-ring chronology which could reflect climate variability in central Scandinavia and possibly also provide a link between Torneträsk and chronologies from central Europe. The selected area, east of the main dividing line of the Central Scandinavian Mountains, seemed ideal: close to the tree line Scots pines of up to 700 years can be found and areas of old-growth forests, virtually untouched by man still exist. But most importantly, large quantities of old pines, preserved for centuries to millennia, were frequently found in small mountain lakes (Gunnarsson, 2001; Gunnarsson and Linderholm, 2002). During the last decade, large efforts have been made to collect Scots pine tree-ring data from living and subfossil wood at a

number of sites in the area, (Gunnarsson, 2001, 2008), and tree-ring width data has been used to reconstruct summer temperatures back to 1600 BC (Linderholm and Gunnarsson, 2005). Furthermore, the temporal distribution patterns of subfossil wood found in various lakes has been used as a high resolution proxy for lake levels fluctuation, which in turn could be coupled to changes in precipitation and changes in the atmospheric circulation (Gunnarsson et al., 2003; Gunnarsson, 2008). In the 1970s, Schweingruber and colleagues collected tree-ring data from Jämtland, producing ring-width and density series covering large parts of the last millennium (Schweingruber et al., 1993; Schweingruber, 1987). This data has been included in reconstructions of large-scale temperatures by Esper et al. (2002); D'Arrigo et al. (2006). However, part of this material has likely been collected from historical buildings, not necessarily from high elevation sites, and consequently the climate information in the data set may be ambiguous. However, progress is being made on updating the density data from tree-line sites (Linderholm et al., 2009; Gunnarsson et al., 2009).

6.3 Finnish Lapland

In northern Finnish Lapland, an abundance of subfossil pines were collected in the beginning of 1970s in order to study pine forests history and tree-line variability (e.g., Eronen, 1982). The tree-ring width chronology contain series from a rather wide region approximately between 68–70° N and 20–30° E, with altitudes ranging between 75–515 m a.m.s.l. The chronology was extended and updated through the Finnish Research Programme on Climate Change (SILMU) and later through the ADVANCE-10K project, with the goal to build a more than 7000-year long tree-ring width chronology for dendroclimatological purposes (Zetterberg et al., 1994; Eronen et al., 1999, 2002). In the early stages of the work, the chronology was not continuous, with an absolutely dated younger part and a "floating" older part, due to difficulties in bridging a 300-year long gap prior to 160 BC. The two chronologies were finally connected in 1999 (Eronen et al., 2002) and is presently is the longest conifer tree-ring chronology in Eurasia extending back to 5634 BC (Helama et al., 2008). This data has been used in several summer temperature reconstructions over different time periods (Linholm et al., 1996; Lindholm et al., 1997; Lindholm and Eronen, 2000; Helama et al., 2002, 2008). However, due to the wide range of sample collection it may be that the homogeneity and the robustness of the data, especially in the older part of the record, is weak (Eronen et al., 2002).

6.4 A regional comparison

The fact that dendrochronological cross-dating is possible between Jämtland and Torneträsk, more than 600 km apart, indicates a common, regional, representative of the high- frequency variability of the two records. However, on longer timescales, periodical differences are evident. A comparison of the two long Swedish tree-ring width chronologies is shown in (Fig. 3). Several synchronous periods have occurred in the nearly 6000 years when the records co-exist. Dramatic shifts from relative warm periods to cold and vice versa (e.g. 3400 BC, 2900 BC and 3600–3400 BC) seem to show better correspondence between the two tree-ring records than complacent growth periods. Generally dry and warm summer conditions prevailed in Fennoscandia between 1800 and 1400 BC. This period was interrupted by a brief period of harsh climate conditions. A marked climate deterioration between 1700–1500 BC is indicated in both datasets. The period 600–1 BC is characterized by low sample replication (not shown here) and high ring-width variability, especially in the Torneträsk record (Grudd et al., 2002). The warm "Roman" period in the first century AD seems to be synchronous in both records. This is interrupted by exceptionally severe summer conditions that occurred around AD 540 and resulted in reduced growth. The "AD 540 event" has been also been found in other paleoclimate data in the Northern Hemisphere (Larsen et al., 2008). The warm period around AD 1000 corresponds well to the "Medieval Warm Period" and is followed by colder conditions, which seems to have started earlier in Jämtland. Both records show a fairly synchronous growth decrease in AD 1550–1700, corresponding to the "Little Ice Age", but this period seems to have been more pronounced and of longer duration in Torneträsk.

7 The atmospheric circulation

Climate variability over the North Atlantic region has been closely associated with the NAO (Visbeck et al., 2001), a mode described as a measure of the strength of westerly winds blowing across the North Atlantic Ocean (e.g., Hurrel, 1995; Slonosky et al., 2000). The NAO, which can be defined as a see-saw of atmospheric mass between the Icelandic low and the Azores high, is most dominant during winter due to the large north-south temperature, and hence pressure, gradients (Hurrel, 1995). During high NAO-index winters, westerly winds are stronger than normal, causing climate conditions over Fennoscandia to be warmer and wetter than usually. During low index winters the westerlies are relatively weak and the influence of cold continental air masses increases in Fennoscandia. Naturally, there has been an interest to extend this large scale feature, with such a pronounced influence on climate in the region, beyond the observational record. Using Scots pine tree-ring data from Norway and Finland, D'Arrigo et al. (1993) found associations between above/below average ring-width departures and positive/negative December–February sea-level pressure (SLP) anomalies related to the Icelandic low. Thus, after cold winters, associated with negative NAO, the trees responded with low growth, and vice versa. This was a first indication that tree-rings could be used to reconstruct winter NAO. Consequently, (Cook et al., 1998) used an extensive tree-ring data set from eastern North America and north-western Europe, including Fennoscandia, to reconstruct the winter NAO. The reconstruction spanned 1701–1980 and explaining 41% of the variance in the observed NAO over the calibration period. Using 30 ring-width chronologies from Fennoscandia, Russia and Estonia, Lindholm et al. (2001) analyzed the sensitivity of Scots pine to seasonal NAO indices. They found that pines in the northern, forest limit, part of the boreal belt were sensitive to summer (June–August) NAO, while pines in the southern boreal belt were responded to winter (December–February) NAO variability. Interestingly, several of the northern chronologies showed as strong, or stronger, correlations with summer NAO as the southern chronologies with winter NAO. Despite that, only winter NAO was attempted to be reconstructed, a reconstruction that explained 25% of the variance in winter NAO. Further improvements of the winter NAO reconstructions were made in subsequent years, combining tree rings and ice core data, eventually extending it back to AD 1400 (Glueck and Stockton, 2001; Cook et al., 2002).

Although most interest in NAO has been in its winter phase, leading atmospheric circulation patterns similar to that of winter NAO are also found in summertime (Hurrel et al., 2003), although the summer pattern has a smaller spatial extent than in winter, and is located further north, with the southern node over North West Europe and a northern node over Greenland. In a recent study, Folland et al. (2009) found strong associations between July–August climate over the western north Atlantic region and the summer (here July–August) NAO (SNAO) on interannual to interdecadal timescales. Positive SNAO is associated with warm and dry conditions over North West Europe but cooler and wetter conditions over southern Europe and the Mediterranean. Using tree-ring data from Great Britain and western Norway, Folland et al. (2009) made a reconstruction of the SNAO back to 1706, explaining 38% of the variance in observed SNAO 1850–1976. The skill of the reconstruction was supported by a strong relationship with Central England temperature remaining strong through the nearly 150 years before 1850. The SNAO reconstruction was further extended back to AD 1441 by Linderholm et al. (2008), based on 37 tree-ring width and density chronologies, mainly from North-Western Europe. On inter-annual timescales, the reconstruction explained at most, with the maximum number of tree-ring series, 46% of the variance in the instrumental SNAO. On periods longer than 10 years, the reconstruction showed more skill, where up to 86% of the variance could be explained. Over the last 550 years the SNAO has been in a negative phase during the majority of the record. Periods of relatively low SNAO in 1650–1750 and around 1800 coincides with periods of very low solar activity (Linderholm et al., 2009), and the strong positive of the SNAO around 1970–1995 seems unprecedented in the last 550 years.

8 Isotope dendroclimatology

As noted previously, climatic information can be extracted not only from widths and density of annual tree-rings, but also from stable carbon, oxygen and hydrogen isotope compositions within the tree rings. However, while various non-climatic factors may influence the growth of a tree (Fritts, 1976), the isotopic ratios in wood are influenced by a limited range of relatively simple physiological controls (McCarroll and Loader, 2004). Thus, there is a large potential for stable isotopes in tree-rings as paleoclimate proxies. Dendroclimatological studies in Fennoscandia, using isotopic techniques, have up to now almost exclusively been restricted to stable isotopes of carbon and focused on trees growing at high-latitude sites in Finland (Fig. 1). The main goal of these studies has to this point been to identify the climate parameters influencing the isotope variability in tree-rings, and to understand the physiological and biochemical processes that influence isotope ratios within a tree. So far, few attempts have been made to use isotopes for climatic reconstruction purposes.

It has been demonstrated that summer sunshine and moisture stress are the dominant controlling factors for $^{13}C/^{12}C$ ratios in late wood cellulose of Scots pine growing in northern Finland (McCarroll and Pawellek, 2001; McCarroll et al., 2003), reflecting the influence of photon flux (sunshine) on photosynthetic rate and moisture stress on reduced stomatal conductance. Gagen et al. (2007) observed high correlations between summer temperatures and the $^{13}C/^{12}C$ ratio in pine, and an attempt was made to reconstruct July–August temperatures. The reconstruction captured a well known cold period in the region and was in agreement with a recent reconstruction of summer temperature from Northern Sweden. In the Central Scandinavian Mountains, Sweden, Seftigen et al. (2009b) have showed that the $\delta^{13}C$ variability in Scots pine is strongly associated to summer temperatures (Fig. 4).

As temperature controls the rate at which photosynthetic enzyme is produced, which is closely involved in the removal of CO_2 from the stomatal chambers during the photosynthesis (Beerling, 1994), it may explain the observed positive relationship between

$\delta^{13}C$ and temperature. Robertson et al. (1997) investigated the influence of climate upon the $^{13}C/^{12}C$ ratio in tree-ring cellulose from oak growing at sites with different hydrological characteristics near its northern distribution limit in southwestern Finland. Results demonstrated a strong negative relationship between summer precipitation/relative humidity and $\delta^{13}C$, and a positive relationship for summer temperature. No intra-site variability in the response of tree-ring $\delta^{13}C$ to climate could however be observed.

Tree-ring carbon isotope values often show a declining trend from the start of the industrial period (~1850), due to incorporation of ^{13}C depleted CO_2 primarily released by the burning of fossil fuels (Freyer and Wiesberg, 1973; McCarroll and Loader, 2004). A correction procedure that attempts to calculate $\delta^{13}C$ values that would have been obtained under pre-industrial conditions was proposed by McCarroll et al. (2009). The procedure, which essentially is a nonlinear de-trending of the low frequency changes in the $\delta^{13}C$ based on the physiological response of trees to rising CO_2, was tested on the $\delta^{13}C$ cellulose data obtained from Northern Finland and North-West Norway. In each case the correction improved the correlation with local meteorological records (McCarroll et al., 2009). Using highly replicated $\delta^{13}C$ chronologies of Scots pine from a number of sites in Northern Finland, Gagen et al. (2008) investigated non-climatic trends in the tree-ring $\delta^{13}C$ series. After a correction for changes in $\delta^{13}C$ of atmospheric CO_2, the chronologies, comprised of 32 trees of several age classes, displayed juvenile trends in absolute $\delta^{13}C$ values lasting for approximately the first 50 years of the tree-growth. The authors showed that Regional Curve Standardization (RCS) approach could be used to identify and remove the juvenile phase, as an alternative to simply omitting the juvenile portion of the stable carbon isotope series. McCarroll and Pawellek (1998) measured the variability and signal strength of $\delta^{13}C$ in late wood cellulose of Scots pine trees growing at sites located along a latitudinal transect, extending from the Arctic Circle to the northern limit of pine distribution, in northern Finland. A strong within and between site signal was observed. However, different trees yielded absolute $\delta^{13}C$ values offset by >2‰, which is similar in magnitude to the variability

within individual series that includes the effect of climate. The authors thus concluded that the common strategy of pooling four cores from four trees is inadequate for paleoclimate research.

9 The temporal strength of climate-signals in Fennoscandian trees

One of the premises to dendroclimatology is that if a growth-climate relationship can be established, this relationship is assumed to be linear over time so that climate can be reconstructed back in time (Fritts, 1976). However, in a high-latitude Northern Hemisphere network of tree-ring density chronologies of conifers exhibiting strong temperature-growth associations, Briffa et al. (1998a) discovered that the chronologies appeared to loose some of their sensitivity to temperature towards the end of the 20th century. Such a "divergence" in the calibration period could lead to reconstructions of temperatures being overestimated, but also that estimates of future atmospheric CO_2 levels, based on carbon-cycle models which are sensitive to high-latitude warming, could be too low (Briffa et al., 1998a). No conclusive evidence of the cause of this divergence has been found, but factors such as increasing CO_2, increased nitrogen fertilization and increased UV-B levels (Briffa et al., 1998b), an increasing trend in winter precipitation in subarctic regions (Vaganov et al., 1999), or increased drought stress due to increased temperatures (Barber et al., 2000) have been suggested. Still, divergence at the end of a chronology may be a methodological problem, either as an effect of standardization (e.g., Linderholm and Gunnarsson, 2005), or the sampling strategy when developing a chronology, where in general old trees are used (see Linderholm and Linderholm (2004), and references therein). Updating the Torneträsk density chronology (see above), Grudd (2008) included relatively young trees in the most recent period, and by doing so the apparent loss of temperature sensitivity in an earlier version was eliminated. Instead, a loss of temperature sensitivity in tree-ring with data in the early nineteenth century was found, likely related to changes in stand dynamics due to a strong regeneration period at that time (Grudd, 2008).

In the Jämtland tree-ring data an anomalous growth increase, which is not seen in the temperature record, occurred around the 1950s (Linderholm, 2002; Linderholm and Gunnarsson, 2005). This growth "surge" was more prominent in the eastern, wetter, part of the sampled region. Despite moderate summer temperatures the pines attained growth levels unprecedented for 320 years. Around this time a nearby glacier experienced a substantial volume loss and Scots pine germination peaked, indicating an extended growing season and likely drier conditions. Similar growth increases around the 1950s were found at sites with a oceanic influence in Norway (e.g., Kirchhefer, 2001; Linderholm et al., 2003), but not at more continental sites, suggesting that only relatively wet sites benefited from a longer and drier growing season.

In a study of conifer chronologies from northern Sweden, Björklund (2009) noted that periodical drops in the correlation between tree-ring with chronologies and observed summer temperatures coincided with drops in correlations among the individual chronologies (Fig. 5). The implication of this is that the validity of multi-chronology reconstruction could be evaluated with running inter-correlation analysis of the included chronologies the entire length of the regional reconstruction.

10 Some future prospects

10.1 Isotopes

While dendroclimatological investigations have utilizing tree-ring width and density to interpret past climate variability, the use of isotope dendroclimatology is more recent. Earlier, work on stable isotopes in tree-rings has been prevented by laborious and time consuming technical procedures, which have constrained a wider application of this methodology. Recent advances in mass spectrometry and sample preparation techniques have however increased the rate at which samples are analyzed, enabling a larger number of samples to be processed and consequently permitting the development of chronologies with a longer temporal range. Improvement has also been

made in understanding how climate and other environmental factors affect the isotopic ratios in trees, which have enhanced the ability to interpret the stable isotope archive (McCarroll and Loader, 2004). This progress had led to an increasing number of isotope studies conducted worldwide, and in Scandinavia several EU-funded projects (e.g. PINE, ISONET and Millennium) as well as national projects (e.g. SweDenClim) contributes/have contributed to an increased number of isotope records for the late Holocene, which will provide valuable information of climate parameters other than temperature.

10.2 Spruce

As shown from this review, Norway spruce has been extensively studied in Fennoscandia, and, as shown by Gouirand et al. (2008), spruce is also highly useful as a regional temperature indicator, possibly superior to Scots pine when tree-ring widths are concerned. In fact, new findings by Björklund (2009) indicate that tree-ring widths from Norway spruce contain a stronger spatial temperature signal than tree-ring widths (Fig. 6).

Since pines are in general better preserved than spruce, Norway spruce has been a neglected species in Fennoscandian dendroclimatology aiming at millennial-scale climate reconstructions. Presently, efforts are being made to create a long Norway spruce tree-ring width and maximum late wood density chronology from the central Scandinavian mountains. New data from Jämtland includes a more than 1000-year long tree-ring width chronology (Gunnarsson, unpublished) which gives a unique opportunity to enhance climate change signal by multi- analysis of coniferous trees and better assess the impact of climate variability on forest ecosystems in the region.

10.3 Teleconnections

Teleconnections, i.e. strong statistical relationships between weather in different parts of the world, in the climate system are associated with the large-scale circulation of the atmosphere and the oceans. In the atmosphere, climate signals can be transferred to regions far removed from the physical source of the variability, while in the oceans teleconnections are associated with the global thermohaline circulation (e.g., Chase et al., 2005). Using high-resolution climate proxies such as tree rings, the spatiotemporal stability of observed climate patterns and associated teleconnections can be studied. As an example, in a study of two millennium-long tree-ring records from Jämtland and Tibet, Linderholm and Bräuning (2006) noted that both records showed similar evolution in tree-growth variability, on decadal and longer time scales, between ca. 1100 and 1550, but around 1550 the two chronologies diverge, possibly due to a strengthening of the Asian monsoon. Feng and Hu (2008) suggested that Temperatures on the Tibetan plateau, which affects the strength of the Asian monsoon, are associated with the Atlantic Multidecadal Oscillation, i.e. sea surface temperature variability in the Atlantic Ocean (Kerr, 2000). The AMO affects climate in the North Atlantic region (Sutton and Hodson, 2005; Knight et al., 2005), and this may account for the long term associations in tree growth between Jämtland and Tibet. Moreover, preliminary results suggest links between the summer NAO, which also is associated with the AMO (Folland et al., 2009), and climate in south-east Asia (Linderholm et al., 2009). This may be related to teleconnections between the NAO and the East Asian jet (Branstator, 2002), where the East Asian jet the strength of the East Asian jet stream affects weather downstream in East Asia (Yang et al., 2002). A new 2.5 millennia long tree-ring record from Tibet (Liu et al., 2009) will facilitate the study of possible teleconnections between Asia and Fennoscandia during the late Holocene.

10.4 Combining tree-ring data and climate models

By virtue of great advances in climate modelling science for recent a few decades, understanding of climate change has been greatly improved. As well as to simulate present-day climate realistically and predict future climate change exactly, a challenging topic of climate modelling is to simulate climate variation in the past. This enables us to better estimate the sensitivity of climate system to the external forcings and to

understand profound mechanism of climate change. The only surrogate to validate the past climate simulation of global climate models (e.g., PMIP2 results) is proxy records from various sources. Tree-ring records provide synthetic information of climate conditions in particular for last a few thousand years with relatively high density over the world, so it has been often utilized to validate climate model's performance in simulating multi-decadal (e.g., PDO , decadal ENSO-monsoon variability) to multi-centennial climate variation (e.g., MWP, LIA). Although there are much uncertainties both in tree-ring records and climate models, it has been suggested that if tree-ring based reconstruction and instrumental records are applied to constrain climate model simulation, we can reduce uncertainties in predicting future climate change (Hegerl et al., 2006). Evolving toward earth system model, most climate models are getting to include fully interactive vegetation models. Tree-ring record can be the most suitable information to validate those model's vegetation dynamics.

11 Some final remarks

As has been shown in this review, the dendroclimatological research in Fennoscandia has contributed to better understanding of late Holocene climate variability in the region. Moreover, some of the data has been used to reconstruct past temperature variability on hemispheric and global scale. Still, Fennoscandia offers large possibilities for future exciting paleoclimate research, e.g. regarding precipitation, humidity and the role of the large-scale circulation on regional to local climate variability. Finally, it should be noted that this review is by no means comprehensive; several works have not been included. This is not because of these works being of less importance, but rather a constraint of time and space.

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Table 1. Fennoscandian stable isotope ($\delta^{13}C$) studies.

Reference	Species	Site	Age-range	Wood component	Signal
Gagen et al. (2007)	12 pines (PS)	2 sites, N Finland	1612–2002	Annual, LW cellulose	Summer temperature
Gagen et al. (2008)	32 pines (PS)	3 sites, N Finland	1780–2002	Annual, cellulose	Summer precipitation, summer temperature, precipitation deficit (sitedependent)
Linderholm et al. (2009)	14 pines (PS)	1 site, W Sweden	1736–2006	Annual, pooled, EW+LW α-cellulose	Temperature >precipitation
McCarroll and Pawellek (1998)	25 pines (PS)	4 and 1 sites from N and W Finland	~1960–1995	Annual, LW cellulose	
McCarroll and Pawellek (2001)	36 pines (PS)	2 sites N Finland	1961–1995	Annual, LW cellulose	Summer sunshine, precipitation (sitedependent)
McCarroll et al. (2003)	10×3 pines (PS)	3 site, N Finland		Annual, LW cellulose	Summer sunshine >summer precipitation >RH
McCarroll et al. (2009)	7 Finnish and 6 Norweigan pines (PS)	N Finland, N Finland NW Norway	1820–2002, 1895–1995 1910–2001	Annual, LW cellulose	
Robertson et al. (1997)	5×2 Oaks (QR)	2 sites, SW Finland	1895–1994	Annual, LW α-cellulose	Precipitation >RH>temperature
Sonninen and Jungner (1995)	1 pine (PS)	Finland	1841–1990	Annual, cellulose	July temperature

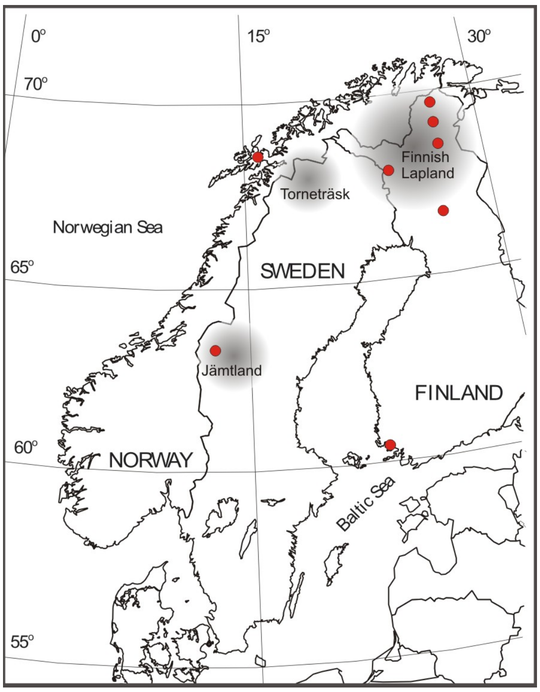

Fig. 1. Map of Fennoscandia with chronologies of multi-millennial extension, Jämtland, Torneträsk and Finnish Lapland, (grey shaded areas), and sites sampled for isotopic chronologies and test studies (red dots).

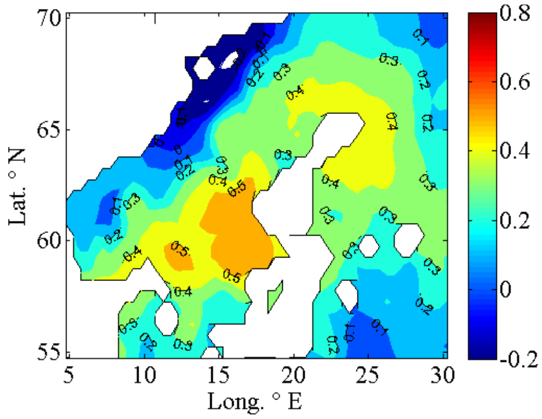

Fig. 2. Spatial correlation between tree-ring PC1 scores, obtained from 5 chronologies in the Stockholm area, and gridded mean May-June precipitation data (CRU TS2.1) (Mitchell et al., 2004) over the AD 1901–1995 period (Seftigen et al., 2009a).

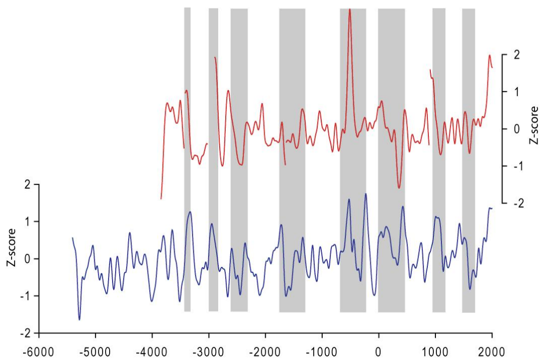

Fig. 3. A comparison between the Torneträsk (blue) and Jämtland (red) tree-ring width chronologies. Both record has been RCS standardized (see text) and transformed into Z-score values, showing centennial variability. Interpreted synchronous periods are shown in grey.

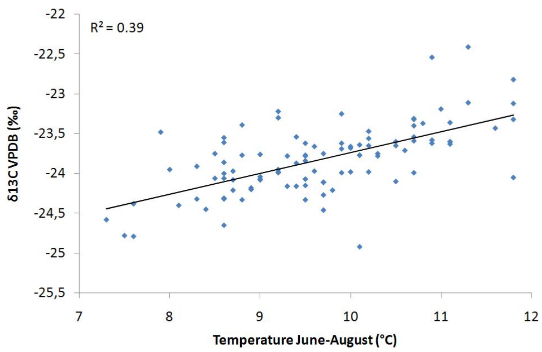

Fig. 4. The relationship between δ^{13}C values from Scots pine growing in the Central Scandinavian Mountains and mean monthly June–July temperature over the 1901–2000 period (Seftigen et al., 2009b).

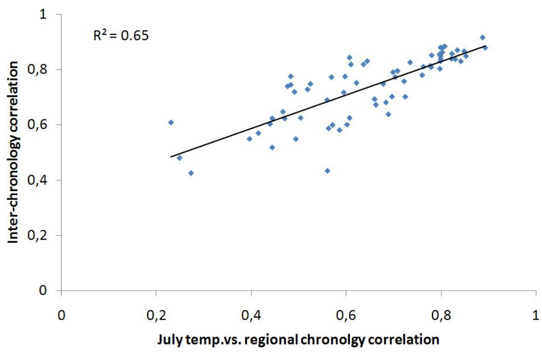

Fig. 5. Running correlations of July temperature vs. a regional TRW pine chronology for Northern Fennoscandia plotted against the mean inter-correlation of the 7 included chronologies of the regional TRW chronology, with a base-length of 11 years and lag of 1 year for the period 1901–1980 (Björklund, 2009).

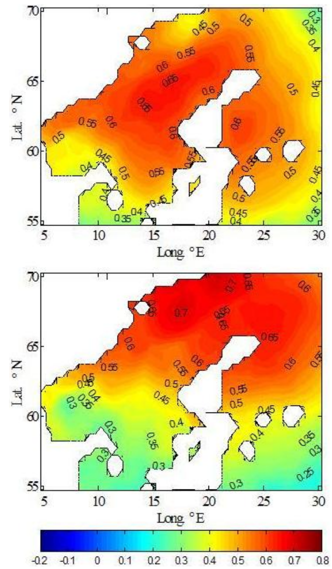

Fig. 6. A comparison of the regional signal in pine and spruce chronologies for Fennoscandia. (On top), spatial correlations of a regional TRW spruce chronology consisting of 1 chronology of 20 series from Arjeplog Lat. 66° N, Long. 17° E, in Northern Fennoscandia against June–July temperature(CRU TS2.1) (Mitchell et al., 2004) from the area above Lat. 63° N, during the period 1901–1980 (Björklund, 2009). (On the bottom), spatial correlations between a regional TRW pine chronology, averaged from 7 chronologies from Northern Fennoscandia, and July temperatures (CRU TS2.1) (Mitchell et al., 2004) from the area above Lat. 63° N, during the period 1901–1980 (Björklund, 2009).