

The influence of elevational differences in absolute maximum density values on regional climate reconstructions

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Abstract

Key message We found that indiscriminately using tree-ring MXD data with inhomogeneous temporal distribution from different elevations might cause biased chronologies. A mean-adjusting method was developed to overcome this bias.

Abstract Here we analyse maximum latewood density (MXD) of *Pinus sylvestris* L. (Scots pine), from deadwood (dry) and subfossil wood (from lakes) collected along an elevation gradient in and close to the central Scandinavian Mountains, in the province of Jämtland, Sweden. Focusing on two common time periods (900–1150 CE and 1300–1550 CE), the mean absolute MXD of deadwood samples showed an inverse relationship with elevation, i.e. the absolute MXD decreases with elevation. However, the MXD values of the subfossil samples did not show such a consistent relationship with elevation. It was also noted that the differences in mean absolute MXD values among sites of different elevations in a given period were larger than among sites of similar elevation between the two time periods, where the former was assumed to be warmer than the latter. Using a theoretical model and a real example, it was shown that indiscriminately using MXD data with inhomogeneous temporal distribution from different elevations may cause biased chronologies, which can have

significant effects on subsequent interpretations of past climate variability. A mean-adjusting method was developed to overcome this bias, and its usefulness was demonstrated by comparing two chronologies built on mean-adjusted and unadjusted MXD samples. It was concluded that unadjusted samples from different elevations with inhomogeneous temporal distribution can distort the long-term trend in a final chronology, while this bias can be alleviated if mean-adjusted samples are used.

Keywords Elevation · Tree-ring MXD · Mean-adjustment · Reconstruction bias

Introduction

Tree-ring data are one of the most widely used proxies to reconstruct late Holocene climate variability with annual resolution. While a common approach is to reconstruct climate from a single site, an increased number of regional reconstructions are emerging. These are either based on averaging of several site chronologies (Gouirand et al. 2008; Cook et al. 2013; McCarroll et al. 2013; Linderholm et al. 2014a) or tree-ring material collected over a larger region (Helama et al. 2002; Liu et al. 2009, Esper et al. 2012a; Melvin et al. 2013). If the region is homogeneous, in terms of climate and growth environments of the sampled trees, it should be expected that the tree-ring data (tree-ring widths (TRW), density, blue intensity or isotopes) should represent a common climate signal. However, if indiscriminately averaging tree-ring data from more heterogeneous regions, e.g. where there is a strong climate gradient or large elevational difference, there is a risk of compromising the sought climate signal if the trees respond somewhat differently to climate.

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A large number of studies have investigated how changes in growth environments, such as degree of continentality, elevation, exposure, etc., affect the climatic sensitivity in tree growth (Schweingruber 1996; Linderholm et al. 2003; Gou et al. 2005). In general, trees growing at their limit of distribution will be most sensitive to climate (Fritts 1976). Thus, as an example, a tree growing at or close to the altitudinal or latitudinal treeline will be sensitive to summer or warm-season temperatures depending on the proxy used. However, trees growing at lower elevations are likely to have a slightly different response to temperature. This is quite clear regarding ring widths (Splechna et al. 2000; King et al. 2013). When it comes to maximum latewood density (MXD), regarded as one of the best proxies for summer temperatures at high latitudes, it has been shown that it has a more coherent spatial signal than TRW, making it ideal for large-scale reconstructions (Briffa et al. 2002). Assuming that MXD from large areas co-vary on annual scale, also along elevational gradients (Splechna et al. 2000), its recognised temperature sensitivity may even be expressed by variations in the absolute density values, e.g. as a function of the temperature lapse rate (or local environment). If so, this could influence composite reconstructions that are based on MXD data from different elevations or different local environments, especially if their temporal coverage is mismatched.

The main aim of this study was, using *Pinus sylvestris* L. (Scots pine) data from the central Scandinavian Mountains, to explore if differences in mean absolute MXD values as a function of altitude are plausible, but also to illustrate the theoretical consequences of combining data with biased characteristics. We show a real example where, if this problem is not addressed, climate reconstructions may be flawed. We discuss how elevational differences in absolute MXD values may affect the temperature signal interpreted from multi-elevation MXD data, as well as propose a method to overcome this problem. As a proof of concept, we utilise a number of heterogeneous MXD datasets from the central Scandinavian Mountains. As the problem of heterogeneous datasets is mainly manifested during 900–1550 CE (when older deadwood is progressively harder to find, and the older samples occasionally are found at above present day tree line), we focused on such a particular case, where two well replicated heterogeneous datasets covering this period were composited with and without taking this potential bias into account.

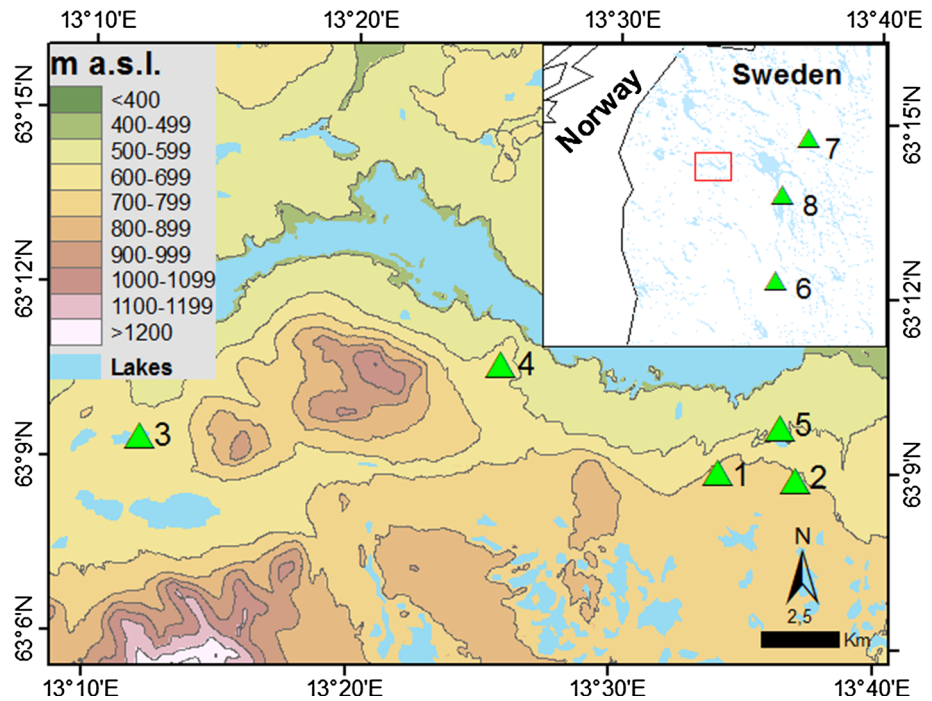
Materials and methods

The samples in this study came from the eastern edge of the central Scandinavian Mountains, in the province of Jämtland, Sweden (Fig. 1). Tree-ring data from this region have

extensively been used, mainly TRW (e.g. Linderholm and Gunnarson 2005; Gunnarson 2008), but lately also MXD (Gunnarson et al. 2011; Björklund et al. 2013). Despite the mountainous environments, the temperature signal in the TRW data is weaker than its more northern counterparts (such as Torneträsk), most likely due to the proximity to and influence of the Norwegian Sea to the west (Linderholm et al. 2003). However, the MXD data has been shown to contain temperature information on par with other Fennoscandian sites (Gunnarson et al. 2011; Björklund et al. 2013). The samples used in this investigation consist of two datasets. The first dataset comprise a subset of MXD data sampled from historical building in the province of Jämtland in the 1970s (Schweingruber et al. 1991; Gunnarson et al. 2011). While the whereabouts of the buildings are known, the timber used for the buildings is not, so the best estimate for the location of the used trees should be close to the buildings, usually well below the present tree line. In this study, we made the assumption that the trees included in the historical data set grew at similar altitudes as the buildings from which the samples were collected. The second dataset comes from samples which have been collected over the last decade, where the majority comes from two sites: Furuberget and Håckervalen, two small mountain ridges ca 6 km apart. At Furuberget, samples were collected from the top of the mountain at ca 650 m a.s.l., corresponding to the present local Scots pine treeline. The growth environment can be characterised as a relatively open pine forest [the average distance between trees is about 10 m, and the forest volume is around 55 forest cubic meters per hectare in the area (estimated from the Swedish national forest inventory (<http://www.slu.se/>))] with thin till and glacifluvial soils, and mosses and woody dwarf shrubs on the ground. From Håckervalen, pine samples were collected from the north facing slope from about 600 m a.s.l. up to ca. 800 m a.s.l. This site has previously been described by Linderholm et al. (2014b). Also, we included some lakewood samples, so called subfossil wood, from nearby lakes which have previously been described by Gunnarson (2008).

The samples were prepared for MXD measurements according to standard dendrochronological techniques (Schweingruber et al. 1978). A thin lath (1.20 mm in thickness) was cut from each of the samples (deadwood and subfossil wood) using a twin-bladed circular saw, and was soaked in pure alcohol in a Soxhlet for at least 24 h to remove extractives such as resin. The laths (air dried to 12 % water content) were then mounted on a sample frame, and X-rayed with a narrow, high energy beam in the ITRAX multiscanner from Cox Analytical Systems (www.coxsys.se), settings according to Gunnarson et al. (2011). A 16-bit digital image with a resolution of 1270 dpi was produced for each sample, and its grey level was calibrated

Fig. 1 Location of the sampling sites (green triangles): 1 Häckervalen, 750 m a.s.l. 53 deadwood; 2 Jens perstjärnen, (lake) 700 m a.s.l. 2 subfossil wood; 3 Öster Helgtjärnen, (lake) 646 m a.s.l. 12 subfossil wood; 4 Furuberget, 650 m a.s.l. 96 deadwood; 5 Lilla-Rörtjärnen, (lake) 560 m a.s.l. 22 subfossil wood; 6 Rätan, 444 m a.s.l. ^a9 deadwood (from historical building); 7 Kyrkås, 341 m a.s.l. ^a19 deadwood (from historical building); 8 Sunne, 320 m a.s.l. ^a8 deadwood (from historical building). ^aCorresponds to the elevations of the historical buildings from which the tree-ring data was derived. These are not necessary the exact elevations of the trees used in the constructions (see text)



using a calibration wedge from Walesch Electronic. The MXD data was obtained from the images using WinD-ENDRO tree-ring image processing software (Guay et al. 1992). The MXD measurements of the historical samples were obtained using DENDRO2003 X-ray instrumentation from Walesch Electronic (www.walesch.ch).

We hypothesized that since MXD is a sensitive temperature proxy, it should not only express information about interannual variations in growing season temperatures, but also relative mean levels of temperature. The different sampling sites were located at roughly the same latitude but at different altitudes, and the local lapse rate in the east central part of Fennoscandia, typically about 0.6 °C/100 meters (Swedish National Atlas 1995), could thus result in slightly different relative means in the MXD data. However, it should be noted that other factors than lapse rate affect micro scale temperatures, such as forest composition, exposure to wind, aspect, etc., could be more critical factors in determining the temperature in a forest. Furthermore, a systematic bias in mean values can occur depending on analysis methodology (Gunnarson et al. 2011; Melvin et al. 2013) and must also, if detected, be addressed when combining proxy data. In order to test the hypothesis, we compared the mean MXD values (absolute measurement values before standardisation) of the 4 groups of samples in the time period 900–1150 CE, and 7 groups of samples in the period 1300–1550. Since the sample depths and age distribution are quite homogeneous among the datasets during the periods of overlap, the mean values of the absolute MXD series should have a limited age bias.

We did not compare the mean MXD values for the 1800–2000 CE period, because this period was only covered by samples taken from approximately the same elevation at both Häckervalen and Furuberget.

Results

MXD mean value differences

Statistics of the different sites are presented in Table 1, and the temporal distribution of the different sampling sites is shown in Fig. 2. The samples were collected from 8 sites covering the period of 799–1764 CE. The elevation ranges from 320 to 800 m a.s.l., where the elevation of the highest samples exceeds the altitude of the present local tree-line (around 650 m a.s.l.) in the area. The samples collected from historical buildings show smaller mean sensitivities than the high-elevation (here defined as the elevation >500 m a.s.l.) samples, which could be partly due to the different MXD measurement techniques but perhaps also due to a more complacent temperature response of the samples caused by their low-elevation (here defined as the elevation <500 m a.s.l.) origin.

From Fig. 3, it is clear that the mean MXD values from trees growing in dry environments (yellow background) decreases with increasing elevation during all sub-periods. The error bars indicate ± two times the standard error of the mean, approximately representing the 95 % confidence interval. Independent sample *t* tests show that the mean

Table 1 Summary statistics of the MXD data

No.	Sampling sites	Elev	TS	NS	MSL	AMXD	MS	AC1
1	Häckervalen	750	799–1520	53	123	0.64	0.128	0.43
2	Jens Perstjärnen ^a	700	1196–1382	2	153	0.62	0.133	0.75
3	Ö Helgtjärnen ^a	646	929–1568	12	110	0.67	0.120	0.68
4	Furuberget	650	837–1764	96	160	0.70	0.122	0.57
5	Lilla-Rörtjärnen ^a	560	952–1686	22	113	0.65	0.122	0.61
6	Rätan ^b	444 ^c	1357–1596	9	186	0.77	0.085	0.67
7	Kyrkås ^b	341 ^c	1332–1609	10	206	0.79	0.084	0.71
8	Sunne ^b	320 ^c	1323–1534	8	163	0.82	0.091	0.61

The two most replicated sites Häckervalen and Furuberget in *bold face* are later used in the real data example of compositing data with different means

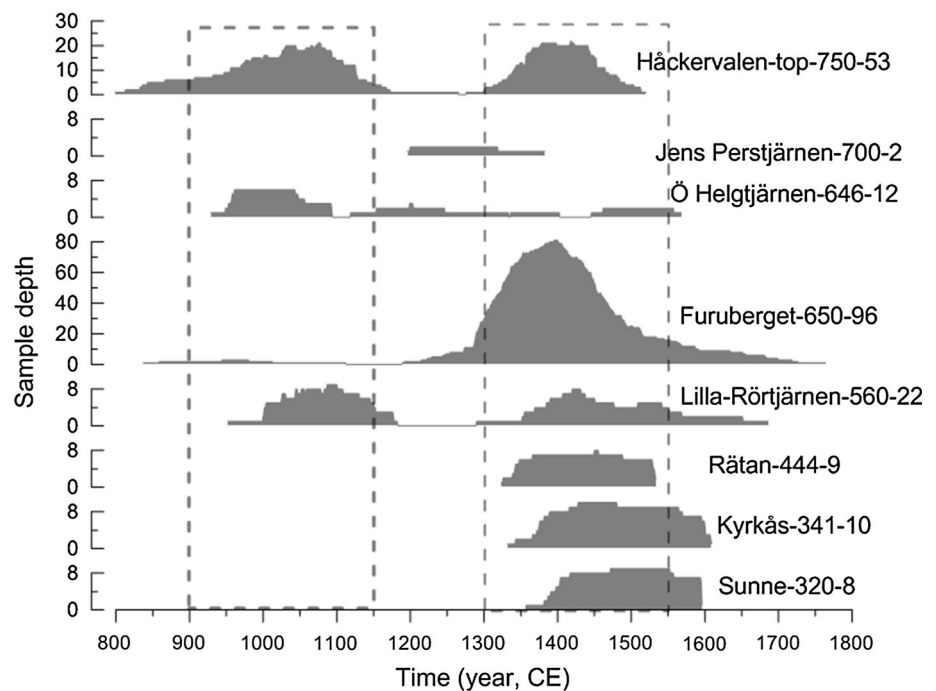
Elev source elevation (m.a.s.l.), *TS* time span (CE), *NS* number of samples, *MSL* mean series length (year), *AMXD* average MXD (g/cm^3), *MS* mean sensitivity, *AC1* first-order autocorrelation

^a The sampling site is a lake

^b The samples are collected from historical buildings in Jämtland, Sweden

^c The elevations of the historical buildings from which the tree-ring data was derived. These are not necessary the exact elevations of the trees used in the constructions (see text)

Fig. 2 Sample replication and time span in each site/group. The site/group names, elevations and the number of samples were given on the upper right corner of each subplot. Dashed line frames mark two common periods with most of the samples. The elevations of site ‘Rätan’, ‘Kyrkås’ and ‘Sunne’ correspond to those of the historical buildings from which the tree-ring data was derived



MXD values at the two high-elevation dry-sites are significantly different ($p < 0.01$) during the periods 900–1150 and 1300–1550 CE. Furthermore, during 1300–1550, the mean MXD values of the deadwood samples at the two high-elevation sites are significantly different ($p < 0.01$) from those at the three low-elevation sites. However, no significant differences in the site-specific means among the three low-elevation sites could be detected, although a tendency to more negative MXD values with increased elevation is seen. Figure 3b shows that the difference

between absolute MXD means at the two high-elevation sites is bigger than that among the three low-elevation sites. MXD from the two wet sites (blue backgrounds) do not show a mean MXD temperature expression that is consistent with lapse rate. Figure 3c shows a synthesis of both periods (without the uncertainty estimates) focusing on common data from four different elevations, and it is clear that for each site, except for the wet site at 646 m a.s.l., Öster Helgtjärnen, the mean absolute MXD values during 900–1150 CE are higher than the period 1300–1550

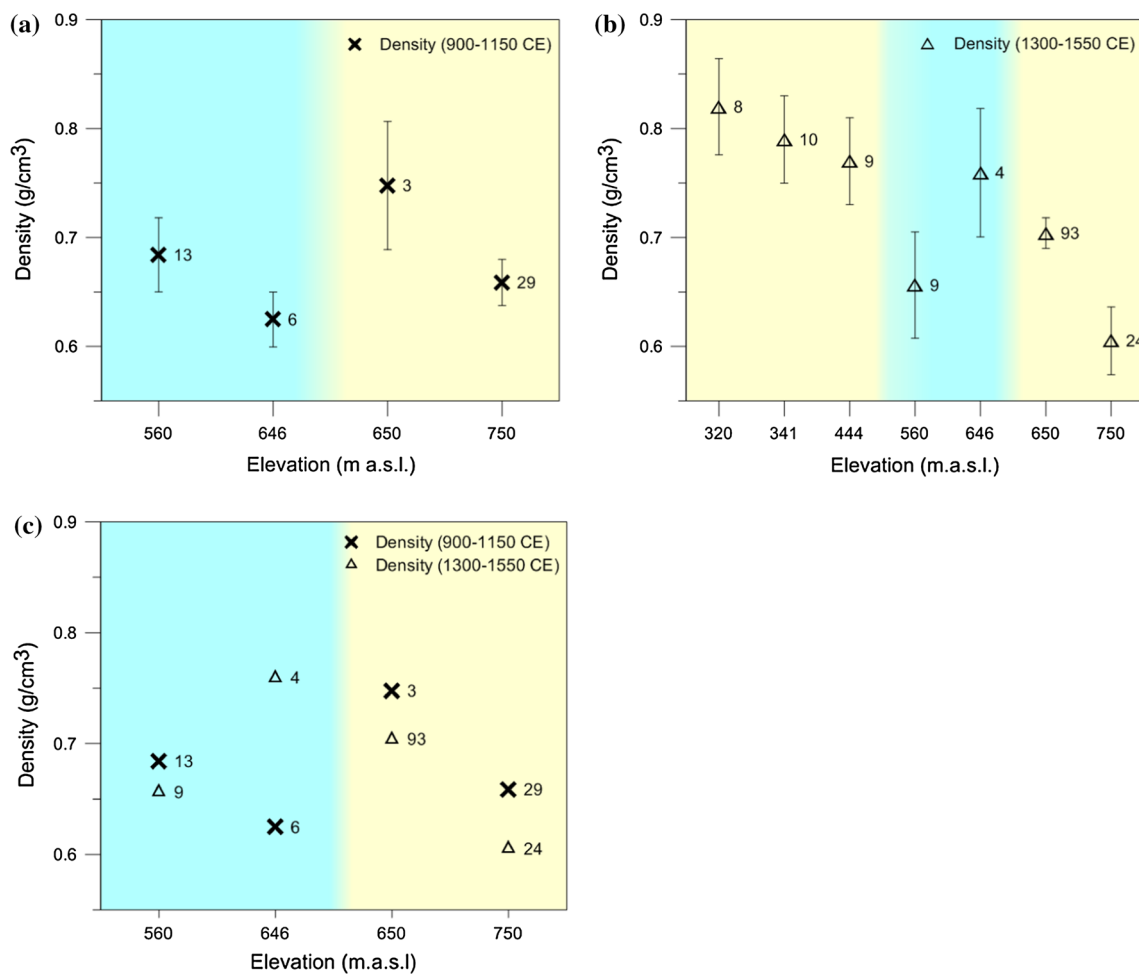


Fig. 3 Comparison of the mean values of the MXD measurements in different sites/groups during the period of **a** 900–1150 CE, **b** 1300–1550 CE. Elevation information was given for each site/group. The error bar shows the two times of the standard deviation. The number of samples was given beside the mean-value makers. Blue and yellow backgrounds indicate the wet and dry

environment. **c** The synthesis plot of (a) and (b) but for four common sites/groups during the period of 900–1150 CE and 1300–1550 CE. The elevations of the dry-site samples from the historical buildings (320, 341 and 444 m a.s.l.) correspond to the elevations of the buildings from which the samples were taken

CE, and the magnitudes of the differences at individual sites are similar to each other, although the mean absolute MXD values are different among the sites during the same time periods. Figure 4 shows that the interannual growth variability is well correlated among most of the sites during the periods of overlap. Despite their low elevation, the historical samples show a coherent interannual variability with the high-elevation samples.

Standardising data from different elevations

Similar to TRW data, MXD data needs to be standardised in order to remove the age effects (Fritts 1976). There are several methods to standardise data, where the aim is to keep as much low-frequency information from the MXD data as possible. One of the most widely used methods is

Regional Curve Standardisation (RCS, Briffa et al. 1992). In this method, instead of using individual curves (e.g. by fitting a function to each MXD series), a regional curve is used to estimate the growth trend of all trees in a group. The regional curve, which is derived from an average of all the individual curves, is then subtracted from each of the MXD series. Since the regional curve does not remove the relative amplitude difference between the series, long-term variability, longer than the trees’ ages can be preserved.

Above it was shown that pines sampled from different elevations differ in mean absolute MXD values, and this needs to be taken into consideration when building a chronology for climate reconstruction purposes. In order to illustrate the importance of adjusting the mean values of MXD data from different elevations, henceforth called mean-adjustment, we start with providing a hypothetical

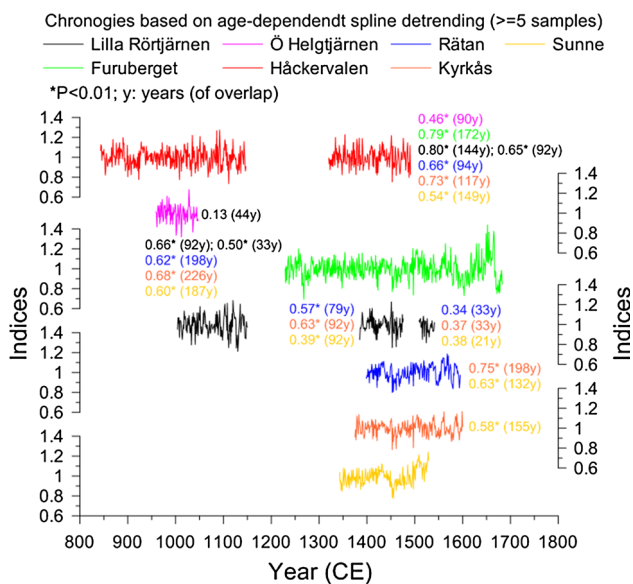


Fig. 4 Correlation coefficient between chronologies during periods of overlap. The *colour number after each chronology* indicates the correlation coefficient between the chronology and another chronology with the corresponding colour. More than one correlation value in one row indicates there is more than one period of overlap between the two chronologies

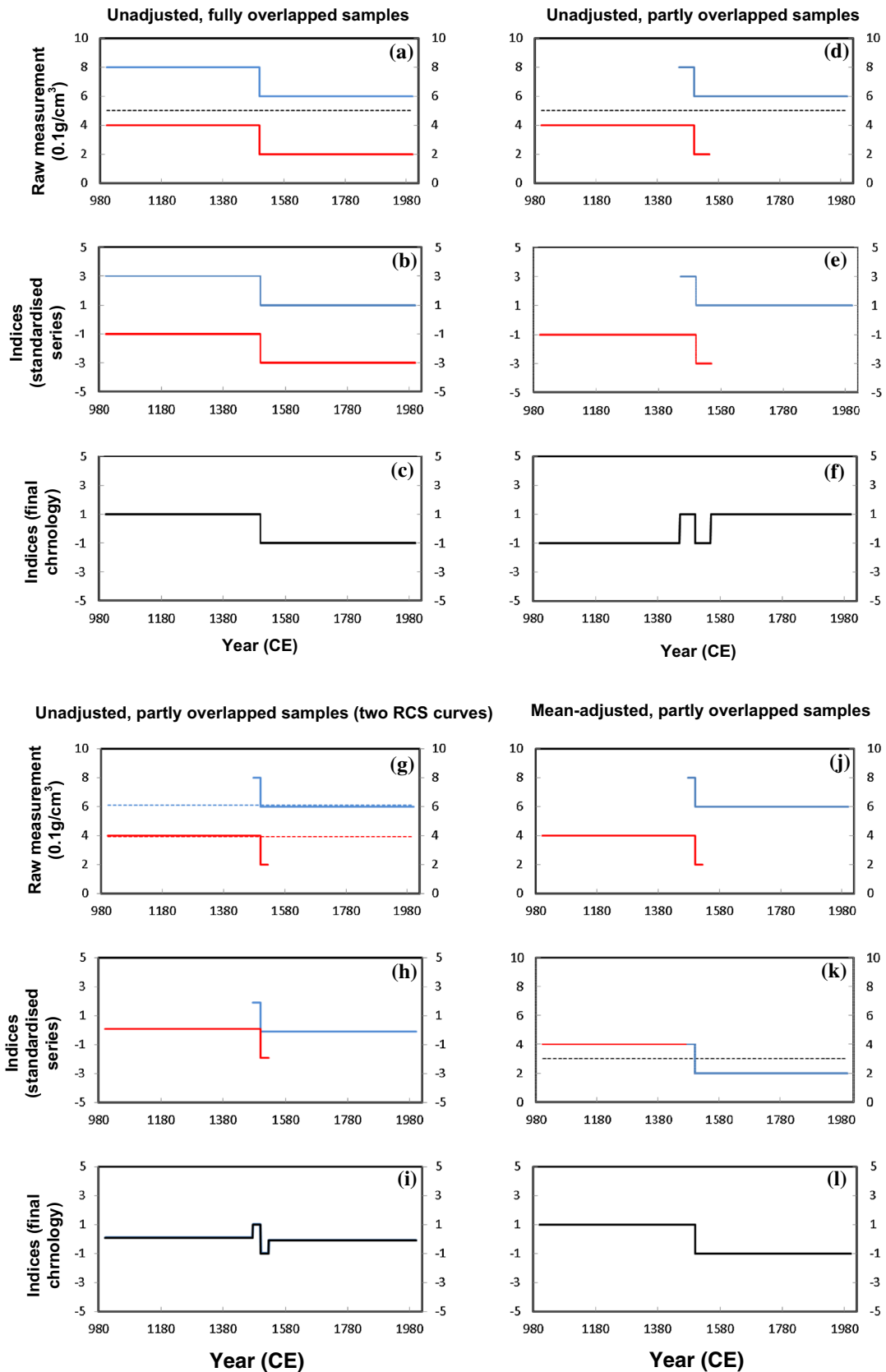
example where we test common standardisation methodologies like RCS (Briffa et al. 1992) or multiple RCS (Melvin 2004; Esper et al. 2012a, 2012b) approaches on theoretical MXD proxy data that capture climate variation perfectly but have different means (Fig. 5). Mean-adjustment refers to the process where the mean MXD values from different elevations are harmonized over well-replicated periods. In the first case we let MXD data from two sites that differ in mean values, perfectly overlap each other in time across a distinct shift in climate. In the second case, they only overlap briefly across the climatic shift. If we create a chronology by combining ‘high’ and ‘low’ mean value sites, when using RCS, the regional curve will be overestimated in relation to the MXD values of the high-elevation samples, and accordingly underestimated in relation to the MXD values of the low-elevation samples (Fig. 5a–d). This difference will be carried over to the MXD indices (Fig. 5b–e). If the samples from different elevations co-exist in time (first example), the under- and over- estimation will be cancelled out, and the elevation bias is not reflected in the final chronology (Fig. 5c). However, if the samples are not temporally coherent, as in the second example, the misestimate will be carried along to the final chronology, which will not represent the ‘true’ climate conditions (Fig. 5f). Even using multiple RCS will create a bias (Fig. 5g–i), but if mean adjustment is applied the full range of the climate shift can be expressed (Fig. 5j–l).

Fig. 5 Illustration of the impacts of using one RCS or two RCS curves to standardise two groups of samples on preserving the climate shift: **a, d, g** two MXD series means (*blue and red lines*) with systematic differences (due to different elevations) showing there is a climate shift (cooling) in 1501 CE; **b, e, h** the two MXD series means after standardisation; **c, f, i** the final chronologies showing three results on preserving the climate shift around 1501 CE. *Dashed lines* represent the mean levels of the RCS curves

When building the west-central Scandinavian Scots pine MXD chronology, which was previously used to reconstruct warm-season (April–September) temperature (Gunnarson et al. 2011), deadwood/subfossil/living samples and historical samples were standardised separately, since the two groups of samples differed in mean and variance. Using different regional curves for samples of different elevation would be a way to overcome the systematic differences in mean MXD. However, if using the same two basic conditions as in the example above (Fig. 5), it would only work if there was a temporally coherent overlap between the two sample populations. If the samples do not overlap sufficiently, the resulting chronology can be severely biased (Fig. 5i).

When applying the RCS method, it is essential that there is no systematic difference in mean and variance between different groups of samples caused by choice of sampling site or measurement methods (Gunnarson et al. 2011). Consequently, we investigated the mean and variance of the samples at the different sites. Focusing on the dry-site samples in a common period (1300–1550 CE), the results suggests no significant difference in variance among the groups using the same MXD measurement techniques, although a slightly increasing trend in standard deviation with elevation was observed (Fig. 6). However, the groups using different measurement techniques (ITRAX and Walesch) show significant differences ($p < 0.01$) in variance.

To overcome the elevation problem without having to resort to several regional curves for the standardisation, we adjusted the means of all groups of samples to the same value based on their relationship during the common period 1300–1550 CE. We used the mean MXD values from Furuberget to adjust the samples from the other groups, because the Furuberget data had a high sample depth and wider temporal coverage than the other groups. A constant was added to or subtracted from all samples from each site in order to harmonize the MXD mean values of the different sites. Because the historical samples show significant differences in standard deviation compared to the Furuberget samples, we adjusted the standard deviation of the historical samples for each of the three sites to force them to have the same mean standard deviation as the Furuberget samples during the period of 1300–1550. As shown in



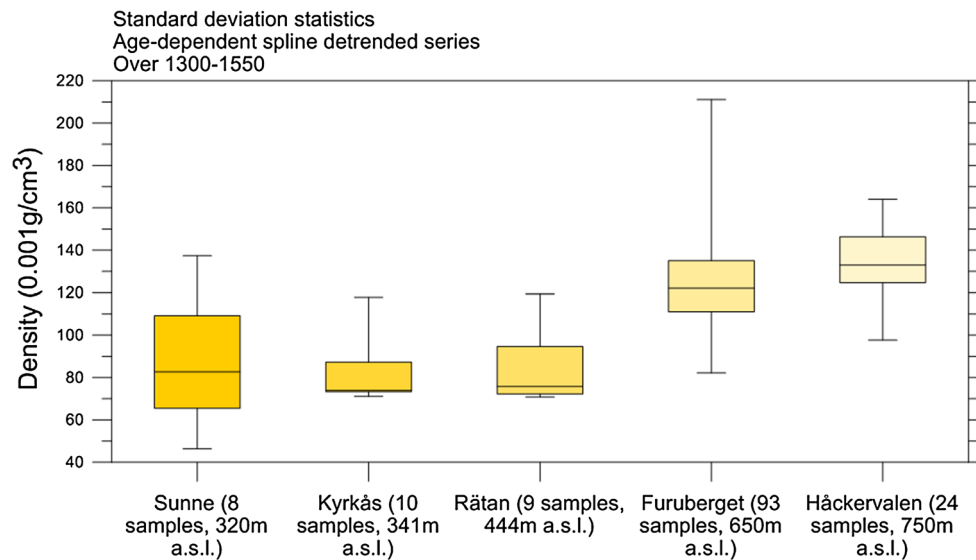


Fig. 6 Box and whisker plot of standard deviation of five groups of dry-site samples (after age-dependent-spline standardisation) during a common time period of 1300–1550 CE. The site/group name, elevation and number of samples were given under each of the plot. Whiskers indicate the minimum and maximum standard deviation of the series in each group, and the upper and lower box boundaries give

the 25 and 75 % statistics. The median values were indicated by the horizontal lines inside the boxes. Deeper yellow colour indicates a higher mean density in a group. The elevations of the dry-site samples from the historical buildings (Sunne, Kyrkås and Råtan samples) correspond to the elevations of the buildings from which the samples were taken

Fig. 6, the mean standard deviation was calculated based on the age-dependent spline detrended series. After adjusting each group of samples, all the samples were merged into one group, and then standardised using the “regional curve adjusted individual signal-free” (RSFi) approach. Following the procedure of Björklund et al. (2013), we produced signal-free age-dependent splines which were aligned according to their cambial ages and forced to have the same mean as their respective cambial age segment of the regional curve [produced by the signal-free RCS method (Melvin and Briffa 2008)]. Then we used these modified splines to standardise the raw measurement data.

Comparing the adjusted and unadjusted chronologies

We have shown that there seems to be a systematic difference in absolute MXD values which likely is related to the elevation of where the trees grow. To illustrate the potential bias on real data, we compared one mean-adjusted and one unadjusted MXD chronology over the period 900–1550 CE. Both chronologies were standardised using the RSFi method. We selected all the Furuberget unadjusted and mean-adjusted MXD indices, and produced two Furuberget chronologies (one is based on unadjusted MXD data, the other is based on mean-adjusted MXD data), and then compared them with the chronologies based on the Håckervalen RSFi indices

(unadjusted and mean adjusted). Figure 7a shows that based on unadjusted data, the Furuberget indices are overestimated compared to the Håckervalen indices, while the Håckervalen indices are underestimated. Although both site chronologies capture a cooling trend, the final chronology based on both sites, actually expresses a positive warming trend. This corresponds to the theoretical example illustrated in Fig. 5, indicating that the bias is due to that the uneven temporal distribution of samples with different site-specific mean values. However, Fig. 7b shows that the trend bias is overcome when using mean-adjusted data. The indices based on the samples from different elevations are not over- or underestimated, and the cooling trend is well preserved in the final chronology based on all samples from both sites.

A comparison of the mean-adjusted and unadjusted chronologies based on all data (including high-elevation and historical samples) is shown in Fig. 8. It is evident that the two curves display striking differences in trends during 900–1550 CE. The unadjusted chronology shows an increasing trend in MXD values corresponding to increasing temperatures, suggesting that the transition from the MCA to the LIA was one from cooler to warmer temperatures. The mean-adjusted chronology, on the other hand, shows more of a cooling trend over this period, which agrees better with the current understanding of summer temperatures during that particular period (Guiot et al. 2005; Esper et al. 2012a).

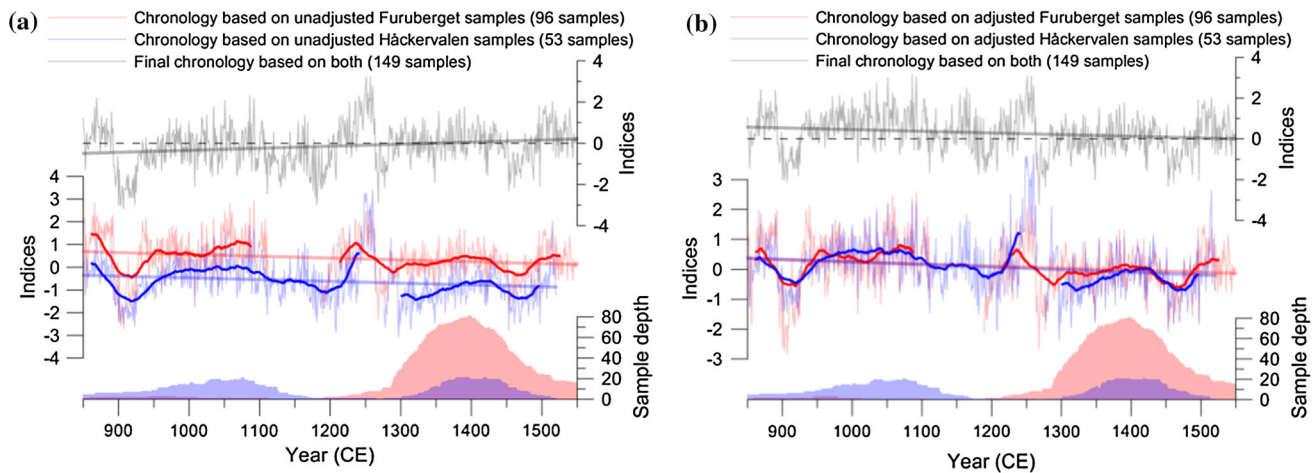
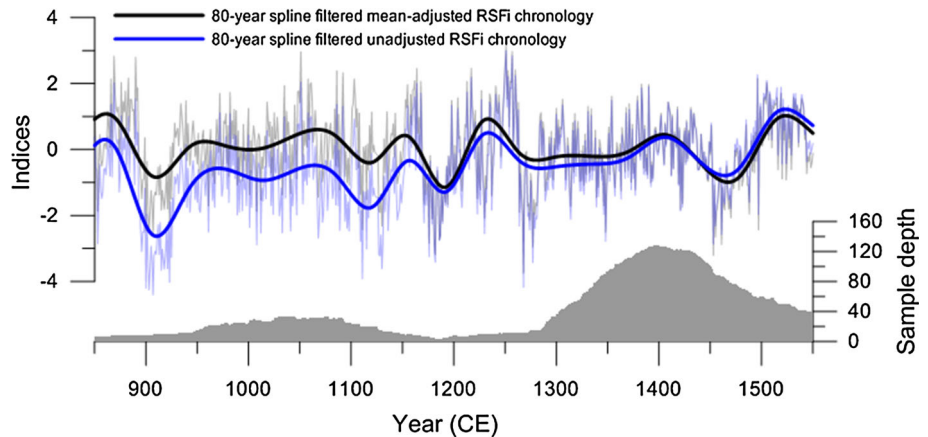


Fig. 7 Comparison between Furuberget (*thin red curves*) and Håckervalen (*thin blue curves*) RSFi chronology based on the indices produced based on unadjusted (a) and mean-adjusted (b) MXD data. *Thin black curves* represent the chronologies based on the indices from both of the sites. *Red and blue shadings* indicate the sample

replication of Furuberget and Håckervalen samples. *Bold red and blue curves* are the 51-year running averaged chronologies. *Bold light lines* indicated the linear trend of the chronologies. *Dashed line* gives a reference of a horizontal level

Fig. 8 Comparison of the mean-adjusted RSFi chronology (*black*) and the unadjusted RSFi chronology (*blue*). *Light curves* indicate the interannual variability, and the *bold curves* show the 80-year spline smoothed variability. The *gray shading* indicates the sample depth



Discussion

The influences of environment

The mean absolute MXD values during 900–1150 CE are higher than those during the period 1300–1550 CE for each site (in Fig. 3c) except for Öster Helgtjärnen. This response in MXD corresponds well with the postulated change in summer climate from warmer conditions during the Medieval Climate Anomaly (MCA, 10th–13th CE, Grove and Switsur (1994)) to cooler conditions during the early Little Ice Age (LIA, 14th–19th centuries, Grove (2001)). Likely the opposite trend visible in the Öster Helgtjärnen data (Fig. 3c) can be attributed to the limited number of samples during 1300–1550 CE (only 4 samples), which is not enough to produce a mean value faithfully representing the mean of the whole population. Our results (Fig. 3c) show

that differences in elevation, local environmental conditions or perhaps measurement technique can create larger MXD fluctuations than those of the temperature evolution from MCA to LIA at each individual site. This implies that in order to attain an unbiased local-to-regional temperature reconstruction, variability for example due to elevational differences in the tree-ring data needs to be taken into account.

The historical samples show coherency with the high-elevation samples at interannual timescales (Fig. 4), indicating that the low-elevation trees are similarly sensitive to temperature as the high-elevation ones. However, the relatively small mean MXD gradient for the low-elevation samples (Fig. 3b), compared to the gradient in the high-elevation samples, suggest that the elevation gradient has a smaller influence on the mean MXD values of the historical samples than on the other dry-site samples. Possibly this is

due to the influences of the micro-local conditions at the sites where the historical samples grew (e.g. close forest and close to human residence).

Still, the discussion regarding the historical data is based on the assumption that the altitudes of the sampled historical buildings were close to those where the utilized trees grew. Due to the lack of any description of the sources of the historical samples, the exact elevation of the trees is unfortunately unknown. However, Tegel et al. (2010) noted that mountainous landscapes with small river systems, i.e. the landscape type of our study area, likely limit wood transportation and floating over longer distances. In our study, the historical buildings were built 400 years ago (according to the dendrochronological dating). During this time, the woody construction materials were usually collected from nearby living trees and left drying for a couple of years. Because people in the mountain valleys lacked efficient transportation capacity, and also that vast forests dominated the landscape from the lowlands to the treeline, it is very likely that the elevation of the source material does not differ to a large degree from those of the sampled buildings.

Because of the limited MXD data from subfossil material at different elevations, we could not systematically investigate the impacts on MXD of local environment for trees having grown on the shores of the sampled lakes. However, from Fig. 3, these trees seem to respond differently, in terms of absolute MXD values, than trees having grown on drier grounds. Likely this is due to the local growth environment, where periodical shifts in lake levels may cause varying responses to temperature in the trees, as has been suggested for TRW (e.g. D uthorn et al. 2013; Helama et al. 2013, Linderholm et al. 2014b). In addition to humidity, other factors such as forest composition, exposure to wind and light, aspect, terrain, etc., can also influence the microclimate. Thus, if we are going to produce multi-millennial MXD chronologies from alpine areas like the Fennoscandian Mountains, if mixing both dry and wet material, as was done by Esper et al. (2012a, b), this particular issue needs to be addressed further.

Influences of measurement technique

Differences in the MXD mean values were detected from the samples at different elevations. The inverse relationship between MXD and elevation is mainly based on the samples from five dry sites/groups (as shown in Fig. 3, yellow background). However, these samples were measured in two different ways. The low-elevation historical samples were measured with Walesch system, and the high-elevation samples were measured with ITRAX system. Thus, potential systematic bias caused by the measurement systems should be clarified. In Grudd (2008), a composite

chronology from Walesch and ITRAX was constructed for a site in northernmost Sweden, the Tornetr sk chronology. Grudd (2008) assessed the differences between the two measurement techniques by measuring one sample with each of the two systems. The results showed that the average MXD was very similar between the two measurements, displaying a difference of only 0.004 g/cm^3 . This difference, if consistent, is insignificant compared to the difference in mean MXD between the historical low-elevation samples and the high-elevation dry-site samples of $>0.1 \text{ g/cm}^3$ (Fig. 3), and suggests a different source of the mean offset than the measurement technique. However, revisiting the Tornetr sk chronology, Melvin et al. (2013) showed by comparing regional curves of the different datasets that the mean difference between the two techniques may be as large as 0.05 g/cm^3 . Therefore, the measurement technique cannot be fully discarded as potential source of the difference in mean of the high-elevation samples and the historical samples. However, the magnitude in the mean offset between the low and high elevation sites in the J mtland material suggests that it is highly unlikely that it can solely be attributed to the measurement technique. Moreover, if measurement technique is partly responsible for the mean difference between the historical and the high-elevation samples, it cannot be the source of bias between the high-elevation samples collected from above and below the present tree line, because these were measured on the same ITRAX device at the Bert Bolin Centre, Stockholm University. Independent sample *t* tests showed that the mean MXD at the two high-elevation dry sites were significantly different ($p < 0.01$), and both of the sites also show significant differences ($p < 0.01$) with the three low-elevation samples.

Another systematic bias generated by the two measurement system is the series variance. The series measured by ITRAX system has a higher standard deviation than that measured by Walesch system (Grudd 2008). The difference can be as large as 0.034 g/cm^3 . Considering this bias, the box plot of standard deviation of the historical samples in Fig. 6 should be lifted to the same level with Furuberget samples, or even higher. Therefore, the significant differences in standard deviation between historical samples and the high-elevation deadwood samples can be mainly attributed to different measurement technique.

The implication of mean-adjustment

The adjustment method developed in this study was called mean-adjustment. The mean values were not only adjusted based on elevation gradient, but actually based on the mean gradient. The phenomenon (mean MXD difference) was found among the samples at different elevations with the deadwood samples' mean values showing a stable inverse

relationship with elevation. We therefore argue that the elevation difference is the most plausible explanation for the absolute mean MXD values as a function of the environment temperature lapse rate. In addition to the elevation difference, we cannot ignore the effects from local environment and MXD measurement technique as described above. However, the mean MXD differences caused by these effects will also be eliminated after the mean-adjustment.

The mean-adjustment method adjusts the mean MXD values at different sites during a common period. It is a fact-based method, and avoids adjusting the mean MXD according to each of environment factors respectively. However, this method requires samples from different elevations to have a common and long enough period of overlap (150 years in our study), and a large enough sample depth to be able to calculate the mean absolute MXD values representative for the populations at each elevation during the common period. However, as mentioned before, the changing elevation of samples mainly occur going back in time, and these old samples could probably form a floating chronology or a chronology with short period of overlap with samples from other elevations. Then it will be difficult to adjust these samples without knowing a clear relationship between MXD and elevations or other environment factors. For instance, in Fig. 7, if the Furuberget and Håckervalen samples had not overlapped, it would have been difficult to adjust these two groups of samples to the same mean level without being able to define the relationship between MXD and elevation. Therefore, the relationship between MXD and elevation and other environment factors (e.g. humidity, since many old samples were collected from lakes which have experienced a wet environment in the past) should be further investigated in future studies.

We have shown that indiscriminately using MXD data from different elevations may cause biased chronologies subsequently used to interpret past climate variability. The problem arises in mountainous regions where the samples covering a specific period can only be found at a certain elevations. In the investigated area in the central Scandinavian Mountains, it may be of particular importance, since deadwood from the MCA can mainly be found above the present treeline, while such material is less likely to be found at lower elevations. This could be due to the temperature and humidity differences leading to, e.g. decomposition or forest composition, but also human activities, e.g. collection of firewood. In anaerobic lake environment, trees are much better preserved than on land. However, possible gaps or differences in sample depth in our chronology can be attributed to fluctuations in water table of the lake and hence, changes in the vegetation at lake shore (Gunnarson 2008). As shown in this study, having a

much higher proportion of either high- or low-elevation trees may cause a biased chronology. Also, much of the really old material (e.g. from the Holocene climate optimum) comes from elevations higher than those of the MCA tree line due to the higher temperature in northern Europe (Davis et al. 2003). Thus, if attempts will be made to create a Holocene MXD chronology from this region, the issue of elevational differences needs to be acknowledged.

Conclusion

The aim of this study was to investigate the potential influences of elevation on MXD values and the potential biases this can cause on chronologies based on multi-elevation samples created for climate reconstruction purposes. Using data from a confined region in the central Scandinavian mountains, we showed that the mean absolute MXD values varied notably with elevation, and that this difference was greater than the difference caused by low-frequency temperature variations (i.e. going from the MCA to the LIA). We showed that without a continuous overlap in samples from different elevations, a chronology may be biased when the data is standardised. To overcome this problem, we advocate mean adjusting the MXD data before standardisation. Our results show that, without mean adjusting, the final chronology based on the samples from different elevations without homogeneous temporal distribution will have a positive linear trend expression on the subsequent temperature reconstruction during 900–1550 CE which is opposite to the negative trends expressed by the chronologies based on the samples from single sites. The positive trend derived from unadjusted material is also contradictory to the indications from other paleoclimate data from Scandinavia and the general idea of northern hemisphere temperature evolution at that time. Moreover, it was shown that MXD from subfossil wood behaved differently from that of trees having grown in drier environments. The nature of this discrepancy is not yet fully investigated, but since much of the pre-CE data in the Fennoscandian Mountains consists of subfossil wood, this is a problem that needs to be acknowledged in future work.

Author contribution statement PZ sampled and prepared parts of the data, designed the analysis, visualized the results and contributed to the writing; JB and HL sampled parts of the data, and contributed to the analysis and the writing.

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Conflict of interest The authors declare that they have no conflict of interest.

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