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Blue intensity and density from northern Fennoscandian tree rings, exploring the potential to improve summer temperature reconstructions with earlywood information

J. A. Björklund[1], **B. E. Gunnarson**[2], **K. Seftigen**[1], **J. Esper**[3], **and H. W. Linderholm**[1]

[1]Regional Climate Group, Department of Earth Sciences, University of Gothenburg, Gotheburg, Sweden
[2]Bert Bolin Centre for Climate Research, Department of Physical Geography and Quaternary Geology, Stockholm University, Stockholm, Sweden
[3]Department of Geography, Johannes Gutenberg University, Mainz, Germany

Correspondence to: J. A. Björklund (jesper.bjorklund@gvc.gu.se)

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Abstract. Here we explore two new tree-ring parameters, derived from measurements of wood density and blue intensity (BI). The new proxies show an increase in the interannual summer temperature signal compared to established proxies, and present the potential to improve long-term performance. At high latitudes, where tree growth is mainly limited by low temperatures, radiodensitometric measurements of wood density, specifically maximum latewood density (MXD), provides a temperature proxy that is superior to that of tree-ring widths. The high cost of developing MXD has led to experimentation with a less expensive method using optical flatbed scanners to produce a new proxy, herein referred to as maximum latewood blue absorption intensity (abbreviated MXBI). MXBI is shown to be very similar to MXD on annual timescales but less accurate on centennial timescales. This is due to the fact that extractives, such as resin, stain the wood differentially from tree to tree and from heartwood to sapwood. To overcome this problem, and to address similar potential problems in radiodensitometric measurements, the new parameters Δblue intensity (ΔBI) and Δdensity are designed by subtracting the ambient BI/density in the earlywood, as a background value, from the latewood measurements. As a case-study, based on Scots pine trees from Northern Sweden, we show that Δdensity can be used as a quality control of MXD values and that the reconstructive performance of warm-season mean temperatures is more focused towards the summer months (JJA – June, July, August), with an increase by roughly 20 % when also utilising the interannual information from the earlywood. However, even though the new parameter ΔBI experiences an improvement as well, there are still puzzling dissimilarities between Δdensity and ΔBI on multicentennial timescales. As a consequence, temperature reconstructions based on ΔBI will presently only be able to resolve information on decadal-to-centennial timescales. The possibility of trying to calibrate BI into a measure of lignin content or density, similarly to how radiographic measurements are calibrated into density, could be a solution. If this works, only then can ΔBI be used as a reliable proxy in multicentennial-scale climate reconstructions.

1 Introduction

Various tree-ring parameters provide annually resolved information on a range of climatic parameters, with measurements of ring widths (TRW) being the most commonly used. In cool temperate climates, the radiodensitometric maximum latewood density parameter (MXD; Schweingruber et al., 1978) has been shown to be a temperature proxy superior to that of TRW (Wilson and Luckman, 2003; Grudd, 2008; Esper et al., 2012b; McCarroll et al., 2013). Producing radiographic density measurements is however both costly and time consuming (e.g. Sheppard et al., 1996). It is also technically challenging, when, for example, it is difficult to fully remove extractives, such as resin, from the wood to produce unbiased radiographic wood density (Schweingruber et al., 1978).

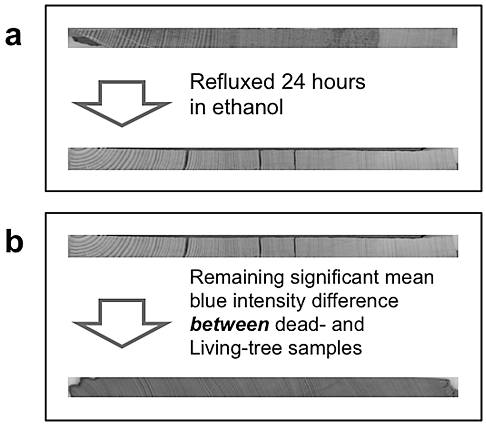

Fig. 1. (a) Sample photos of living-tree samples before and after alcohol soxhlet extraction. This shows a stark contrast in blue intensity between untreated and refluxed samples. **(b)** Example of two cores, one living tree sample and one log sample, the latter died around 1650. This also shows a stark contrast between dead-tree samples and living-tree samples suggesting that dead-tree samples are more permanently discoloured than living-tree samples. The red and green colour spectrum is filtered out of the photos, leaving only the blue spectrum that is represented in greyscale.

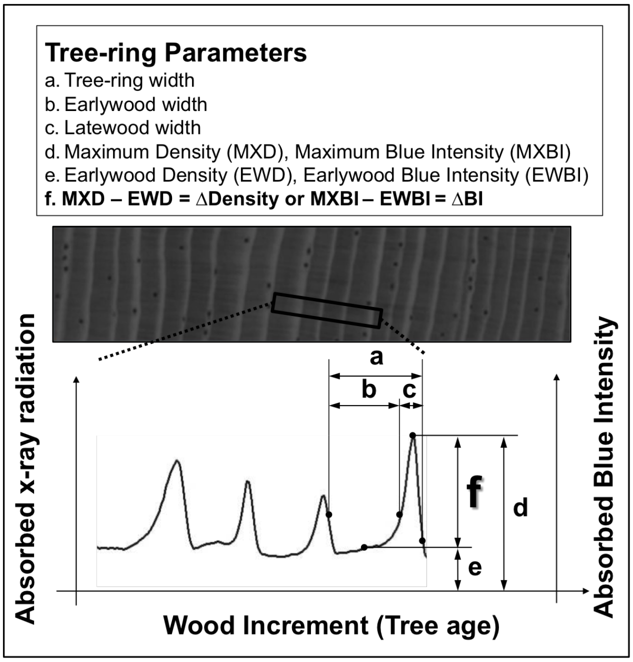

Fig. 2. Schematic figure of different tree-ring parameters to show the relation of the new previously unexploited ∆density- and ∆BI-parameters to the more familiar parameters TRW, MXD, etc. Note that the blue intensity parameters are using the radiographic image, which is essentially similar to an optically scanned image.

An optical alternative to radiodensitometry is the blue intensity technique (BI; see overview in Campbell et al., 2011), where the minimum blue reflectance or intensity has been shown to be highly correlated with corresponding MXD values. Consequently, the BI proxy has been suggested to be a potential surrogate for MXD at a significantly lower cost (McCarroll et al., 2002; Campbell et al., 2007). However, the technical difficulty associated with extractives is potentially more pronounced when optical flatbed scanner images are analysed. Incomplete removal of extractives will have large effects on BI measurements for some conifer tree species, partly because their woody tissue is divided into differentially coloured heartwood and sapwood (Fig. 1a), but also because there is natural variability in extractives among trees/samples (Fig. 1b). Hence there is a great need to address this issue for BI and to revisit the potential biases that this could cause in radiodensitometric measurements.

1.1 Radiodensitometry and blue intensity

The radiodensitometry method is based on the detection of residual x-ray radiation emitted through a tree-sample of known depth. The radiographic greyscale values are subsequently transformed to wood density by calibrating them with a “standard” of cellulose acetate (Schweingruber et al., 1988), a compound with properties similar to the structural wood components of lignin, cellulose and hemi-celluloses (see Supplement Fig. S1a for the relationship between radiographic measurements and radiodensitometric values).

Similarly, the BI technique is based on the detection of reflected visible blue light, but there is not yet a “standard” available to calibrate the BI measurement into any structural component of the wood. McCarroll et al. (2002) argued that the variation in BI is mainly caused by the lignin in the wood, which is a very effective absorber of short wavelength energy (deStevens and Nord, 1951; Schubert, 1965). Tracking the radial profile in the wood, wood density changes considerably across annual rings (from earlywood to latewood), while the mass ratios of lignin, cellulose and hemicelluloses are almost constant (Michael Jarvis, personal communication, 2013). So, even if the variation in BI is not solely a function of lignin content, the other potential increment-specific candidates that could cause variation in BI will co-vary with lignin. Hence, a very close relationship between the radiodensitometric and BI proxies should be expected. Nevertheless, we henceforth refer to the BI target as “lignin-content” due to the uncertainty regarding what BI measures.

While radiographic images are inverted so that the x-ray greyscale represents the absorbed x-ray radiation which is positively correlated with wood density, BI images are usually not (Campbell et al., 2011). However, it can be argued that BI images should also be inverted to represent the absorbed blue intensity, in order to be positively correlated with “lignin-content” (Supplement Fig. S1b–e). This would simplify the nomenclature and we therefore propose that maximum latewood blue absorption intensity (MXBI) rather than *minimum blue intensity* (Campbell et al., 2011) should be used, as it is a more intuitive counterpart to MXD (see

Supplement for other technical software-related advantages). Consequently, both MXD and MXBI measurements represent the peak values in the latewood each year (Fig. 2). Likewise, measurements of earlywood density (EWD) or earlywood blue absorption intensity (EWBI) can be calculated as the mean value over the earlywood width.

The incomplete extraction of non-structural compounds such as oils, gums, resins and tannins can offset the radiographic density/structural wood density by adding mass to the cell-wall structure (Schweingruber et al., 1978) and also offset the BI/"lignin content" by staining the cell walls (Fig. 1). When McCarroll et al. (2003) suggested that MXD represents a proxy measure of net photosynthesis over the entire growing season, they specifically meant that the *structural wood density*, and not the non-structural extractives, is the measure of the photosynthetic production. The contributions from the extractives to MXD or MXBI are not related to photosynthetic activities allocated to specific increments, but rather they represent a response to environmental stress and are freely distributed across ring boundaries (Schweingruber et al., 1978). The latter potentially becomes a problem because of the fact that the woody tissue of many coniferous tree species is divided into heartwood and sapwood due to the differential allocation of extractives towards the heartwood (Raven et al., 2004), and if this is not accounted for then a systematic bias is introduced. Moreover, some trees within the same species may produce more extractives than others due to stress or just natural variability. If such trees are not distributed randomly in time, then a similar systematic bias in a climate proxy chronology can occur.

1.2 Objectives

To address the issue of biased radiodensitometric/optical measurements, we utilise a newly sampled, highly replicated, multigeneration, > 800-year-long *Pinus Sylvestris* L. (Scots pine) chronology from northern Fennoscandia. Both optical and radiographic measurements are made on the *same* cores to directly evaluate their relationship and their climatic signals. A novel approach designed to address the brightness and potential wood density bias in the heartwood/sapwood boundary and among samples is introduced. This method relies on the assumption that the biasing effect is of equal magnitude in the increments of earlywood and latewood. The difference between latewood and earlywood is calculated to give the latewood measurement a baseline, here termed Δdensity for radiographic measurements and ΔBI for optical measurements. This exercise was previously considered in another form (as a *ratio* between latewood and earlywood brightness) by Sheppard et al. (1996) to address optical distortion in *photographic* images of wood. However, Sheppard et al. (1996), and later McCarroll et al. (2002), considered this methodology inadequate. Here we show the merits of these new parameters by (1) addressing the biasing effects from substances not related to wood structure in both radiographic and optical measurements, and (2) by introducing a new climate proxy where the earlywood measurement is also integrated to potentially improve reconstructions of northern Fennoscandian summer temperatures (JJA – June, July, August).

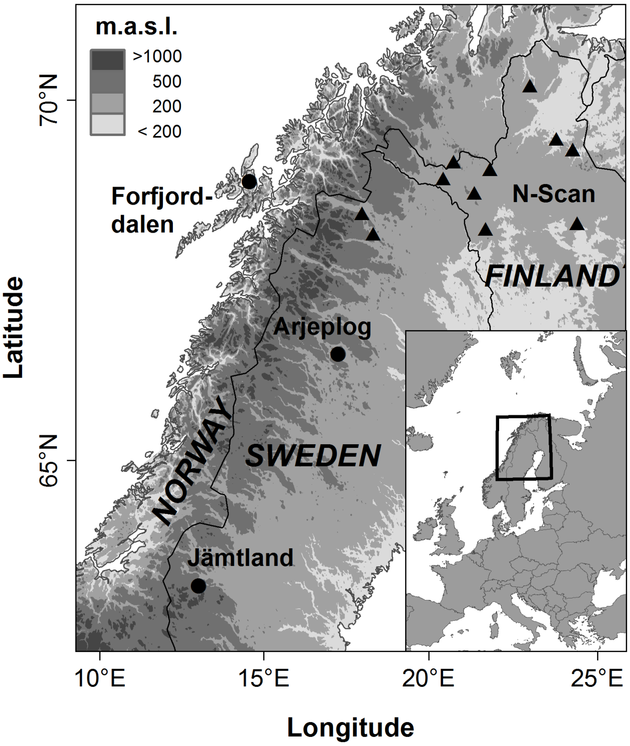

Fig. 3. Filled circles indicate the Arjeplog site produced for this study, as well as Jämtland (Gunnarson et al., 2011) and Forfjorddalen (McCarroll et al., 2013). Triangles are the sub-sites included in the N-Scan chronology (Esper et al., 2012a). Jämtland, Forfjorddalen and N-Scan are used as reference chronologies in this study.

2 Data and methods

2.1 Study area

A site in Northern Sweden (66°2′ N, 18°1′ E), 50 km north of the town of Arjeplog, was sampled for Scots pine (Fig. 3). The source area for the sampled trees is a north-facing slope of a mountain reaching an elevation of 800 m where pines, together with sparse *Betula pubescens* Ehrh (Downy birch), form the tree line at 700 m a.s.l. The climate in the area is cool and temperate with mean monthly temperatures ranging from −14 °C in January to 13 °C in July and a mean annual precipitation of 553 mm (Arjeplog meteorological station, 1961–1990 period; data from the Swedish Meteorological and Hydrological Institute).

2.2 Tree-ring data

Although optical and radiographic measurements were made on the same cores, it should be noted that measurement tracks differ slightly. This could have a minor effect on individual measurement series, and mean chronologies from the two methodologies cannot be expected to be entirely identical.

The radiodensitometry data was produced using an Itrax multiscanner from Cox Analytical Systems (www.coxsys.se). The samples were prepared according to standard techniques (Schweingruber et al., 1978) following the protocol outlined in Gunnarson et al. (2011). The optical data was produced using the standard protocol according to Campbell et al. (2011), with the modifications outlined in the Supplement. The digital images were produced with a flatbed scanner at 1600 dpi (dots per inch) resolution (Epson Perfection V600 Series) calibrated with SilverFast Ai professional scan software using the calibration target IT8.7/2. All radiographic and optical images were analysed through the commercial software WinDendro™. The parameters used were MXD, EWD and Δdensity (the difference between MXD and EWD) as well as MXBI, EWBI and ΔBI (the difference between MXBI and EWBI) (Fig. 2).

To further evaluate the new methods, three neighbouring radiodensitometric reference chronologies were used (Fig. 3): N-Scan (Esper et al., 2012b); Forfjorddalen (McCarroll et al., 2013) and Jämtland (Gunnarson et al., 2011). Forfjorddalen and Jämtland were also analysed with the Itrax system while N-Scan was analysed using the Walesch system (Esper et al., 2012b).

2.3 Climate data

In order to identify and evaluate climate signals in the tree-ring data, response function analyses were made using the DENDROCLIM2002 software (Biondi and Waikul, 2004). The 2.5° gridded mean land temperature CRU (Climate Research Unit) TS3.1 data set (Harris et al., 2013) was used and each chronology was compared to the temperature record from the grid box encompassing it. The common overlap between the chronologies and observational data (1902–2006) was used in all climate response function analyses. The response function analyses were made using first-differenced proxy and instrumental data. This process removes all variation on the medium and low frequency bands to prevent biased correlations due to spurious similarities in trends (cf. Cook and Kairiukstis, 1989). A more exhaustive climate correlation of the standardised Arjeplog chronologies is presented in Supplement Figs. S2 and S3 to facilitate the assessment of the high- and mid-frequency correlations with temperature and precipitation.

2.4 Comparative analyses

A simple set of comparative analyses was utilised in this study. Pearson correlation coefficients were calculated with first-differenced tree-ring data sets, while the lower frequencies were only evaluated visually. Chronology confidence was evaluated using the expressed population signals (EPS; Wigley et al., 1984), where the EPS value quantifies how well the sample represents the whole population of trees. This was calculated in this study for 50-year moving windows with a 1-year lag. Values above 0.85 are generally considered adequate. Traditional regional curve standardisation (RCS; Briffa et al., 1992) and data-adaptive curve fitting (DACF) using age-dependent smoothing splines (Melvin et al., 2007) were used to evaluate climate-reconstructive performance in the optically derived chronologies. The standardisation was performed with the ARSTAN software (Cook and Krusic, 2005).

2.5 Δdensity and Δblue intensity, two previously unexploited proxies

If untreated with alcohol, the heartwood and sapwood will have very different colours, and this visual colour difference is reduced, but not removed, after ethanol reflux (Fig. 1a). When extraction is incomplete the colour difference between heartwood and sapwood causes a stepped offset in the BI measurements at the transgression boundary. Furthermore, Fig. 1b shows that colour differences may be even larger among samples, than within samples with heartwood/sapwood, which could cause further offset biases through time. These offsets may also be present in radiodensitometric measurements, but are usually too small to be noticeable.

If the offsetting extractives are present in equal magnitudes in earlywood and latewood, it enables a correction of ambient discoloration by simply subtracting the mean earlywood measurements from the maximum latewood measurements. The earlywood values provide a baseline for the more dominant signal carriers MXD and MXBI. According to this reasoning, the previously unexploited parameters Δdensity and ΔBI were constructed (Fig. 2). The method was tested on the radiodensitometric reference data, firstly by high-frequency climate sensitivity with response functions analysis, and secondly by a visual inspection of annual-to-centennial-scale co-variability. The hypothesis was that if Δdensity has an equally robust and plausible climate signal as MXD, then the method could be used to evaluate systematic biases in radiodensitometric and optical measurements, thus providing a new proxy for climate reconstructions.

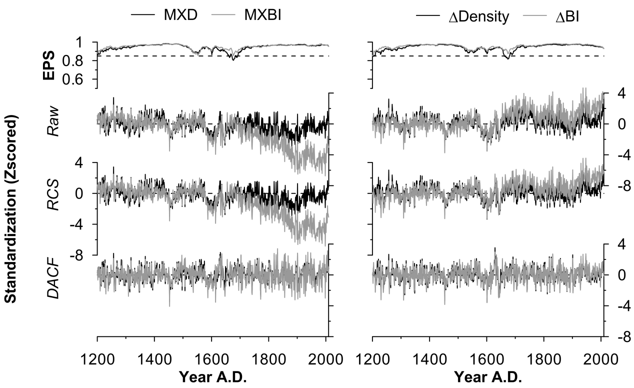

Fig. 4. MXD, MXBI and Δdensity and ΔBI chronologies with expressed population signal (EPS). Raw chronologies are averaged without standardisation and RCS chronologies have been developed using a single regional curve, allowing indices to have different means but still being able to represent climatic differences without general age effects (Briffa et al., 1992). DACF chronologies are standardised with data-adaptive curve fits using time varying response smoothing described in Melvin et al. (2007). The DACF removes mean differences between the resulting indices and is also able to remove more non-climatological variability within each sample.

3 Results

The MXD and MXBI chronologies have sufficient EPS values for the entire analysed period, except for one segment around AD 1600 in the MXD data (Fig. 4). The first-differenced MXD and MXBI chronologies correlate at $r = 0.95$, and the Δdensity and ΔBI correlate at $r = 0.97$ ($n = 810$). A visual examination of the common variability on centennial timescales shows that the raw and the RCS MXD and MXBI chronologies co-vary from AD 1200 to AD 1700 (Fig. 4, note that all chronologies were z-scored using this reference period). After this, there is a large negative divergence in the MXBI chronologies. The DACF MXD and MXBI chronologies co-vary throughout their length, but MXBI displays an increased variance in the modern period. The raw and the RCS Δdensity and ΔBI also co-vary from AD 1200 to AD 1700. After this time, the two proxies start to diverge, but the (positive) divergence in the ΔBI data is not as pronounced as in the previous case. The DACF Δdensity and ΔBI chronologies co-vary well (Fig. 4).

Examining the Δparameter and its relationship to its components MXD and EWD using the radiodensitometric material, it is evident that the variability in MXD is large compared to EWD (Fig. 5). This means that MXD will dominate the Δdensity parameter. Examining the optical measurements, the variability in MXBI is not as large relative to EWBI, and the optical measurements exhibit much smaller variability than the radiodensitometric measurements (Fig. 5). The variation around the mean values are however larger for the BI method, considering the smaller standard deviations (Supplement Fig. S4a–b).

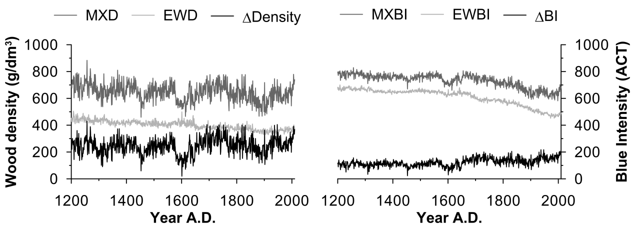

Fig. 5. Left-panel chronologies are mean EWD, MXD and Δdensity. Right-panel chronologies are EWBI, MXBI and ΔBI. The chronologies are raw data; no standardisation has been applied. The blue intensity data is produced using an adjusted colour target IT8/7 (ACT) (see Supplement Fig. S1). The variance is much larger in MXD and Δdensity compared to MXBI and ΔBI. However, the spread of series-mean values is relatively larger for the blue intensity data (see Supplement Fig. S4).

The MXD shows positive and significant ($p < 0.05$) responses to April–August temperatures at all sites, except for June at Forfjorddalen (Fig. 6). EWD also responds positively to April–May temperatures but flips to a negative response in June and July. Δdensity has no significant response to April (on average) and a low but significant response to May, accompanied by a strong June–August response. The BI and radiodensitometric material from Arjeplog have almost identical response signals. Using first-differenced data, the JJA signal strengths increase on average by 20 % when using Δdensity instead of MXD (Table 1).

All reference MXD and Δdensity chronologies display very similar variability at annual to centennial timescales, although there is a slight difference in the overall trend in the Arjeplog chronologies (Fig. 7).

4 Discussion

The level of correlation between MXD and MXBI, and Δdensity and ΔBI is very high. However, it is clear that MXBI is affected by additional factors that make the proxy diverge from MXD at centennial timescales (Fig. 4). The 300-year divergence between MXD and MXBI is not only a product of the heartwood/sapwood difference in BI, but probably also results from the differential staining among samples, which creates a large spread in mean values relative to the small standard deviations (Supplement Figs. S4b, S5). Figure 1b indicates that the modern or living-tree samples are brighter than the older snag material on average (see Supplement Fig. S5, where the mean and standard deviation of the MXBI and EWBI measurements combined are regressed against time. Note that this analysis was made without the lighter sapwood material). If it was the heartwood/sapwood transition that was important in creating this large divergence, it would have begun around the turn of the 20th

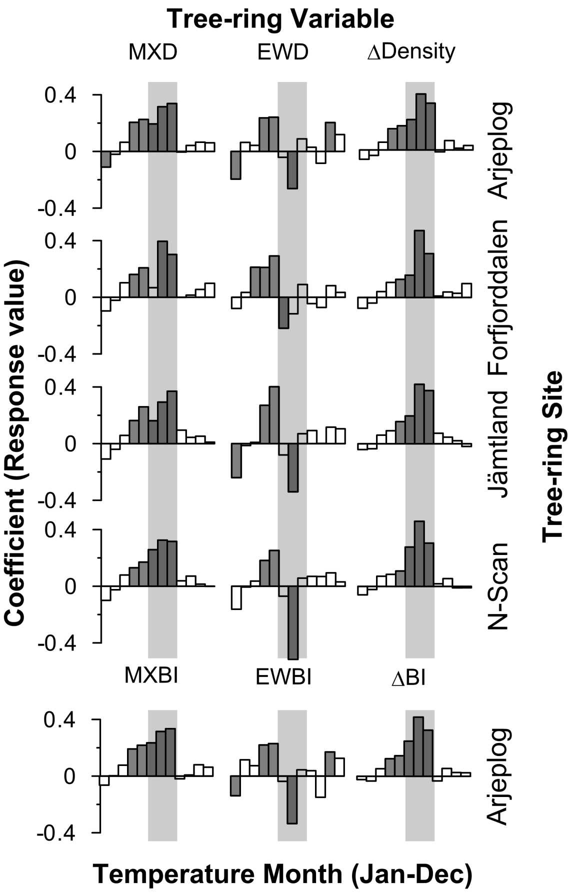

Fig. 6. Monthly temperature response on different tree-ring parameter chronologies from Arjeplog, Forfjorddalen, Jämtland and Finland N-Scan. All chronology and temperature data are transformed into first differences thus only taking the high frequency response into account. Grey-shaded areas demarcate the summer months (JJA).

century when almost all sapwood-material was introduced (Supplement Fig. S7), instead of beginning around AD 1700. However, the importance of the heartwood–sapwood transition is indicated by the increased variance in the modern part of the DACF MXBI chronology and the fact that the divergence in the RCS chronology reaches its maximum around the turn of the 20th century. We suspect that the differential staining, manifested as a large spread in the mean BI values of samples, is a result of an extended residence time of oils, gums, resins and tannins in the wood that yields a more permanent discolouration. We conclude that there is a systematic bias in the BI (at least for this population sample) that likely also includes an age component. Better methods to neutralise these compounds are therefore needed and longer treatment times for older material should perhaps be considered in future work.

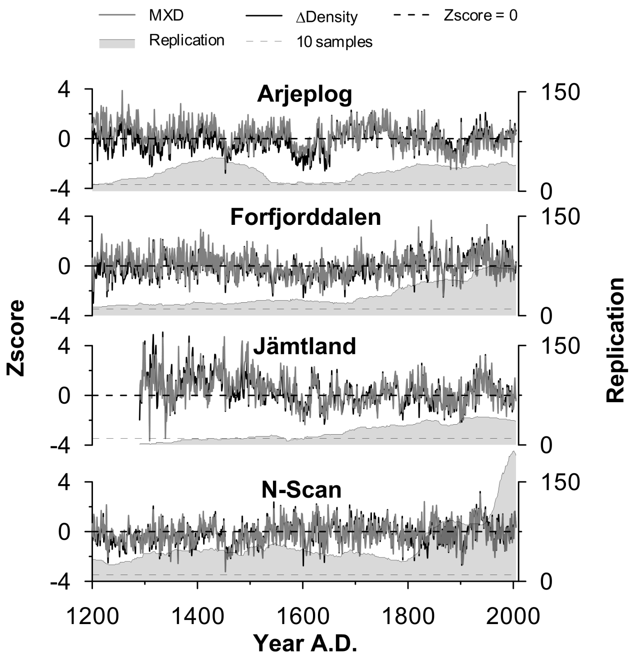

Fig. 7. Raw MXD chronologies in grey plotted together with raw Δdensity chronologies in black. The three reference chronologies Jämtland, Forfjorddalen and N-Scan have very similar MXD and Δdensity counterparts. Note that the Arjeplog MXD and Δdensity chronologies have visible differences in trends. Grey-shaded areas indicate sample depth through time, and light-grey-dotted lines indicate 10 samples.

4.1 Exploring the Δ parameter using radiodensitometric data

The climate responses of the four MXD chronologies to April–August temperatures are consistent with many other studies of MXD from the region (e.g. Briffa et al., 2001; Björklund et al., 2013). It has been suggested that MXD represents a proxy measure of net photosynthesis over the entire growing season (McCarroll et al., 2003). However, it may be questioned whether April should be included in the growing season since mean temperatures in Arjeplog are around 0 °C. Nevertheless, Salminen and Jalkanen (2007) noted apical cambial activity in Scots pine at these latitudes around the end of April, which is possibly why temperatures in this month control density as well.

The less-investigated parameter EWD showed a positive response to temperatures in April and May, but a negative response in July. The highest growth rates of the cells in Scots pine at these latitudes occur in July (Hustich, 1956; Schmitt et al., 2004; Seo et al., 2008), so our interpretation is that if July is warm, then large cells are produced, resulting in less dense wood. The lignification of the cell wall completes the maturation of a tracheid just after the cell formation (Wight, 1933; Gindl et al., 2000), so if April–May is warm, then higher lignin content in the cells is likely. Consequently, the

Table 1. Explained variance (R^2) in JJA temperatures from MXD and Δdensity as well as MXBI and ΔBI. Temperature data from CRU TS3.1 data set (Harris et al., 2013). All chronology and temperature data are prior to analysis transformed into first differences, to remove positive autocorrelation.

Chronology/parameter	MXD	ΔDensity	MXBI	ΔBI	Increase*
Arjeplog	0.50	0.59	0.54	0.62	15 and 13 %
Forfjorddalen	0.47	0.61			23 %
Jämtland	0.51	0.65			22 %
N-Scan	0.53	0.66			20 %

* Increase refers to the change between MXD and Δdensity in explained variances of JJA temperatures as well as for MXBI and ΔBI, respectively.

earlywood cell walls would become thicker and the earlywood denser. Thus EWD and MXD seem to share a positive spring temperature response. If the lignification is considered as the total collection of assimilates during the growing season, the response would likely be similar in EWD and MXD. However, EWD only responds to spring while MXD responds to both spring and summer, suggesting that the MXD measurement is intraseasonally autocorrelated with EWD. Subtracting the earlywood measurement from the maximum latewood measurement should thus weaken the April–May Δdensity signal (shown in Fig. 6). The difference in sign in the response to July between EWD and MXD is likely related to EWD being more cell-size dependent, while MXD is more dependent on cell-wall thickness. The Δdensity parameter response to July becomes strengthened since the effect of the cell size variation and early season lignification is removed, resulting in a more focused summer temperature response.

However, MXD and Δdensity still share most of their variation. Equivalently, mean April–August temperatures share most of the information with the mean in June–August, and we therefore anticipate that MXD and Δdensity should be very similar on all timescales, and even more on longer timescales. This is supported by the fact that the N-Scan, Forfjorddalen and Jämtland Δdensity chronologies are almost identical to their MXD counterparts (Fig. 7). Since these chronologies do not diverge in any respect, the potential biasing effect from extractives is concluded to be negligible. However, in the Arjeplog chronology there is a visible drift between the MXD and Δdensity chronologies, although the annual variability is almost identical (Fig. 7). This is likely a sign of biased radiodensitometric measurements where oils, gums, resins and tannins have had a significant influence also on the wood density. Using EWD to calculate Δdensity could thus act as a quality control for MXD. In conclusion, the Δdensity parameter clearly contains plausible information and can be used for further analyses of blue intensity data.

4.2 The ΔBI parameter

The bias in brightness with respect to time is very strong in the BI material, whereas modern MXBI values are frequently of the same magnitude as older EWBI values (Fig. 5). The frequency distributions of densitometric measures and BI measures are also clearly very different (See Supplement Fig. S4a–b ii). The MXBI and EWBI chronology counterparts have steep negative trends suggesting that the earlywood and latewood are similarly discoloured, which is why ΔBI appears to be a promising solution. However, Fig. 4 shows that the resulting ΔBI chronology has a much more positive trend than the corresponding Δdensity chronology. This is surprising considering the very similar climate signals and the degree of high-frequency correlation ($r = 0.97$) between the two proxies. If the Δ parameter were able to neutralise the discolouration in the BI measurements, and the resulting measure is a reflection of “lignin content”, then the chronology would likely be more similar to the Δdensity chronology. It is very unlikely that there would be a long-term trend offset between the two Arjeplog chronology signals described in the climate response function analysis in Fig. 6. Further, if ΔBI represents “lignin content” and Δdensity represents wood density, it is hard to understand how these parameters could diverge through time.

An explanation for this could be that the assumption of equal discolouration in earlywood/latewood is invalid and/or that the BI measurement should be tied to “lignin content” with calibration, similar to how radiographic measurements are tied to wood density. Indeed, a representative BI sample from Arjeplog seems to have a non-linear relationship with the radiographic wood density of the same sample (Supplement Fig. S6, lower panels). Since “lignin content” and wood density are so tightly coupled (Michael Jarvis, personal communication, 2013), it is very likely that BI also needs to be calibrated in some way to accurately reflect “lignin-content” values. Further studies are needed to evaluate this possibility.

Using DACF standardisation (Cook, 1985), ΔBI is an excellent climate proxy, equally strong to Δdensity. However, if composite detrending methods such as RCS are considered, then entirely differing trends are retained in the Δdensity and ΔBI chronologies, respectively. This would therefore result in entirely different views of how the 20th century climate is placed within this 800-year context. This divergence is likely a result of biases inherent to the ΔBI data, rather than Δdensity, and the low frequency trends indicated by

RCS-based reconstructions from such data would be difficult to trust at this point.

5 Conclusions

Based on the Arjeplog Scots pine samples, our results suggest that the critical obstacles in trying to create a high-quality climate reconstruction based on blue intensity are the heartwood–sapwood transition and the differential discoloration between wood samples. Furthermore, radiodensitometric measurements can likely also be biased due to the insufficient extraction of movable compounds such as oils, gums, resins and tannins even though recommended protocols are followed. The Δ parameter can be used to identify problems with radiodensitometric measurements, assuming that Δdensity can be treated as an alternative or complement to MXD if a shorter target season is required. A noteworthy feature of the new Δdensity parameter is that it includes information from the whole ring (also the earlywood), which is more intuitive and informative than only using the MXD.

The Δ parameter only partly works for blue intensity; using ΔBI, high-quality decadal-to-centennial-scale climate reconstructions can be obtained but > centennial timescales appear to have additional biases. Since the BI is so much more inexpensive than its radiodensitometric counterpart, finding a solution to these biases is worth pursuing. If successful, this could result in a considerable improvement of the spatial distribution, and replication, of highly climate-sensitive tree-ring chronologies, thereby increasing confidence of large-scale climate reconstructions.

Supplementary material related to this article is available online at http://www.clim-past.net/10/877/2014/cp-10-877-2014-supplement.pdf.

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