Dendrochronologia 61 (2020) 125706

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro

Original article

Delta blue intensity vs. maximum density: A case study using *Pinus uncinata* in the Pyrenees

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ARTICLE INFO

Keywords:
Delta blue intensity
Pyrenees
Pinus uncinata
Summer temperatures

ABSTRACT

We explore the potential of the delta blue intensity (DBI) parameter as a proxy of past summer temperatures using a well replicated (85 trees) chronology of *Pinus uncinata* from upper treeline in the Spanish Pyrenees. Principal component analysis, correlation response function analysis and Superposed Epoch Analysis show definitively that the DBI data are indistinguishable to other MXD datasets in the region and that DBI expresses a similarly “pure” time-stable climate signal as MXD when compared to their RW counterparts. Calibration r^2 values > 0.5 are attainable depending on period used. The signal strength of DBI data is weaker than MXD and behave more like RW data with ca. 19 trees being needed to attain an EPS value > 0.85. However, as the generation of DBI data is cheaper than MXD, this limitation is not deemed to be a serious issue. This pilot study suggests that robust reconstructions of past summer temperatures could be gained using DBI data at a much-reduced cost than relying on MXD. Future dendroclimatic efforts in the region therefore should focus on the measurement of this parameter and the expansion of the *pinus* ring-density network.

1. Introduction

Tree-rings are invaluable archives of past climate for the late Holocene due to their exact annually resolved dating control (Stokes and Smiley, 1968; Anchukaitis et al., 2012), the generally good understanding of the processes governing tree growth (Fritts, 1976; Körner, 2003; Vaganov et al., 2006, 2011; Rossi et al., 2013) and their ability to express a range of different climate variables (Schweingruber, 1988; Jones et al., 2009). Different parameters can be measured from the rings of trees including width, density, wood anatomical properties and stable isotopes (Speer, 2010; Björklund et al., 2019), the variability of which can represent varying climate signals which are often moderated by site ecology. For example, a rough rule of thumb is that the growth of trees growing at high elevation/latitude environments will be temperature limited (Fritts et al., 1965; Kienast et al., 1987; Briffa et al., 2002) while at low elevations/latitudes moisture availability becomes the primary driver of productivity (Fritts, 1976; Cook et al., 2004, 2015). More complex associations exist for stable isotopes (McCarroll and Loader, 2004).

For the reconstruction of Northern Hemispheric (NH) summer temperatures, tree-ring records hold particular prominence for the last 1000 – 2000 years (Masson-Delmotte et al., 2013; PAGES 2k Consortium, 2013; Esper et al., 2018). To date, large compilations of temperature sensitive tree-ring data have mostly focussed on both ring-width (RW) and ring-density parameters (Esper et al., 2002; D’Arrigo et al., 2006; Stoffel et al., 2015; Wilson et al., 2016; Anchukaitis et al., 2017) with notable exceptions using only maximum latewood density (MXD - Briffa et al., 2001; Schneider et al., 2015). RW data correlate moderately with summer temperatures (Briffa et al., 2002; Wilson et al., 2016) and generally express strong persistence (i.e. high 1st order autocorrelation) which may impart spectral biases in the resulting local and large-scale temperature estimates (Franke et al., 2013, Lücke et al., 2019). MXD, on the other hand, often matches better the autocorrelation structure of the target summer temperature data (Ljungqvist et al., 2020). In an ideal world, therefore, chronology development (new and updates) should focus on MXD, with RW being used cautiously so long as the spectral properties of the reconstruction matches the instrumental data target. The new generation of tree-ring only NH reconstructions (Schneider et al., 2015; Stoffel et al., 2015; Wilson et al., 2016) represent a substantial improvement on earlier attempts (Briffa et al., 2001; Esper et al., 2002; D’Arrigo et al., 2006). However, despite many studies over the last 20 years definitively detailing that MXD is the more robust parameter (Briffa et al., 2002; Wilson and Luckman, 2003; Esper et al., 2012; Büntgen et al., 2017; Ljungqvist et al., 2020), there has been no community wide strategic plan or investment to update datasets sampled in the 1980s/90s (Schweingruber and Briffa,

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https://doi.org/10.1016/j.dendro.2020.125706
Received 13 January 2020; Received in revised form 23 March 2020; Accepted 30 March 2020

1996). Rather, those relatively few important millennial long MXD records that have been developed or updated, represent individual laboratory efforts to create improved regional records (Luckman and Wilson, 2005; Büntgen et al., 2006; Esper et al., 2012; McCarroll et al., 2013; Zhang et al., 2016; Büntgen et al., 2016, 2017; Esper et al., 2019). Presumably, this reflects the relatively small number of tree-ring laboratories with densitometric equipment (Wilson et al., 2014, 2017a) and for this situation to change, a more affordable method is needed that all laboratories can embrace and utilise.

Since the initial concept paper (McCarroll et al., 2002), measurement of the intensity of the reflectance of blue light from the latewood of conifer samples (often referred to as blue intensity (BI)) has shown great promise as a surrogate and cheaper replacement of MXD (Björklund et al., 2014, 2015; Rydval et al., 2014; Wilson et al., 2014). MXD and BI measure similar wood properties – the relative density of the latewood of conifers - and are well correlated with warm-season temperatures. Most studies that have compared MXD and BI directly show no significant difference between the two parameters (Wilson et al., 2014; Ljungqvist et al., 2020), although in one study BI was found to express temporal instabilities compared to MXD (Kaczka et al., 2018). Despite the ever-expanding number of papers using BI, it must still be seen as an experimental parameter as it has only been utilised on a relatively small number of conifer species (e.g. *Pinus Sylvestris*, Scotland, UK (Rydval et al., 2014), and Scandinavia (Campbell et al., 2007, 2011; Helama et al., 2013; Björklund et al., 2014, 2015; Fuentes et al., 2018); *Picea engelmannii*, the Canadian Rockies, British Columbia, Canada (Wilson et al., 2014); *Picea abies*, Europe (Österreicher et al., 2015; Buras et al., 2018; Kaczka et al., 2018; Rydval et al., 2018); *Abies nordmanniana* in the Northern Caucasus (Dolgova, 2016); *Pinus ponderosa*, American SW (Babst et al., 2016); *Pinus cembra*, Austria (Wilson et al., 2017a); *Tsuga mertensiana* (Bong. Carrière), Gulf of Alaska (Wilson et al., 2017b); *Fokienia hodginsii*, central Vietnam (Buckley et al., 2018); *Larix decidua Mill*, Europeanm Alps (Arbellay et al., 2018); *Callitropsis nootkatensis (D. Don) Oerst. ex DP Little,* Gulf of Alaska (Wiles et al., 2019); *Picea glauca*, the Yukon (Wilson et al., 2019)). There is no theoretical reason why BI should not produce similar results for any species from which MXD data have been measured (Björklund et al., 2019). However, the most significant limitation of BI is the fact that it is based on light reflectance. Any colour change on the surface of the wood samples that does not represent year-to-year climate driven latewood cell wall relative density changes (e.g. heartwood/sapwood colour change, or fungal-related discolouration) will impart a potential low frequency bias into the raw measurement data. A proposed method to correct for such biases subtracts the raw latewood minimum BI value from the maximum earlywood BI value (Björklund et al., 2014), producing the so-called Delta BI (DBI) parameter. Compared to standard latewood BI, DBI has only been tested on *Pinus sylvestris* (Björklund et al., 2014, 2015) and *Tsuga mertensiana* (Wilson et al., 2017b). Herein, we detail a small-scale study that tests DBI on *Pinus uncinata* samples from the Spanish Pyrenees by comparing the data with archived MXD chronologies from the surrounding region.

2. Data and methods

From previous experience working in Scotland, NW North America and the Carpathian Mountains (Rydval et al., 2014, 2018; Wilson et al., 2014, 2017a,b, 2019) a single well replicated tree-ring site should allow a robust test of the viability of BI as a climate proxy for any conifer species in a region. This is based on the consistent observation that BI expresses a "purer" summer temperature signal and is less impacted by site ecological (e.g. disturbance) effects than RW. Following this hypothesised approach, we targeted an upper tree-line site in the upper Aranser valley of the Spanish Pyrenees and cored 85 trees of the species *P. uncinata* (Fig. 1). Previous work in the region has highlighted the greater strength of MXD data as a proxy of summer temperatures over RW (Linán et al., 2012; Büntgen et al., (2008); 2017). For comparative analysis, three archived MXD datasets, within 120 kms of the Aranser valley, were accessed from the International Tree-Ring Databank (ITRDB – Fig. 1). These three sites represent similar upper tree-line sites and therefore the trees should express a similar climate response to those at the Aranser study site.

The Aranser tree cores were slowly air dried and as this pine species shows a notable colour change from heartwood to sapwood, the samples were immersed in acetone for 72 hours to remove resins in the wood (Rydval et al., 2014). The samples were sanded to 1200 grit and scanned at 3200 dpi resolution using the Silverfast scanning software, calibrated with the IT8.7/2 colour card. Latewood minimum BI and maximum earlywood BI values were measured (see Rydval et al., 2014 for details) using the CooRecorder 8.1 software (Cybis 2016 – http://www.cybis.se/forfun/dendro/index.htm) and the DBI values calculated (Björklund et al., 2014).

Fig. 1 shows three example scanned cores after resin extraction treatment. Although resin extractives have theoretically been removed, the wood can still be discoloured by other non-climatic related effects. Samples UAV05 and 15, for example, show dark fungal related staining that was not removed by the acetone treatment. Sample UAV12, despite immersion in acetone, still shows a subtly darker heartwood compared to the sapwood. These colour differences impose systematic biases in the raw reflectance intensity measurements and so the DBI variable will be utilised hereafter as these biases should theoretically be removed or minimised.

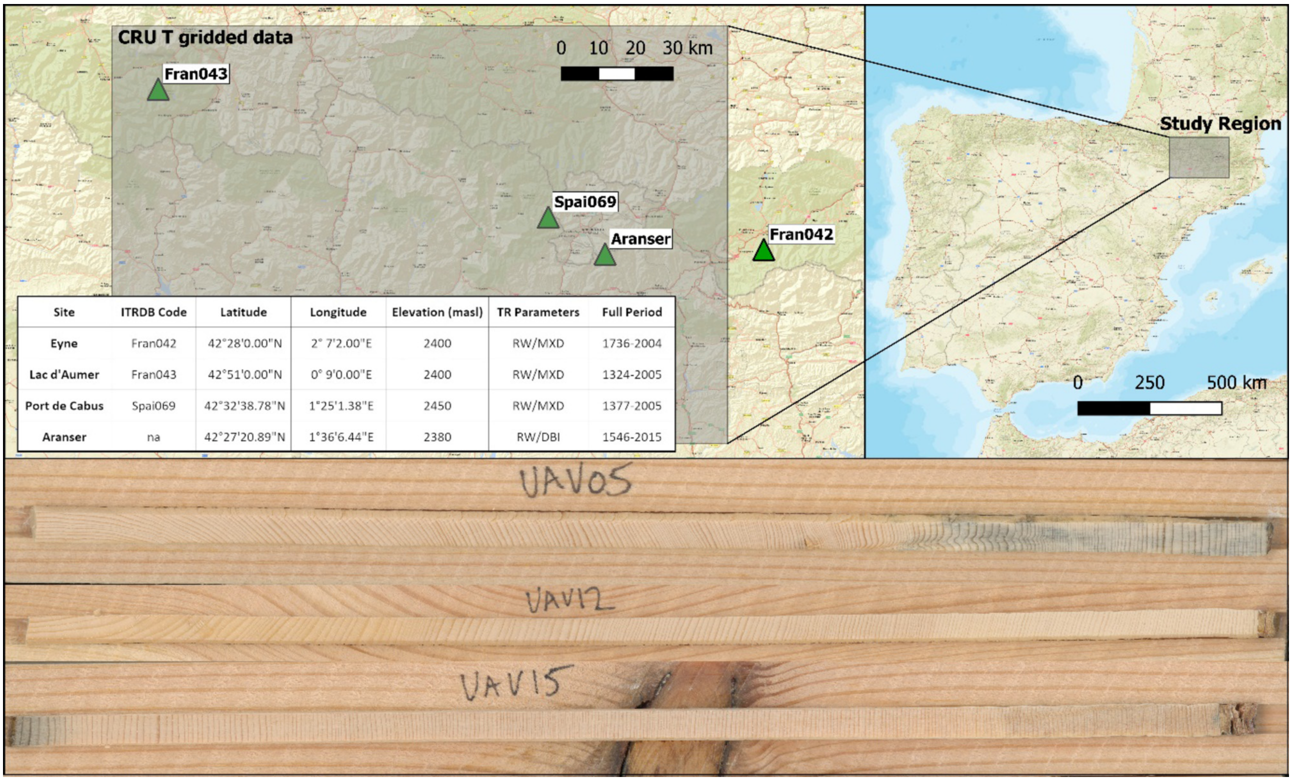
Based on standardisation experiments from white spruce RW and latewood BI data from the southern Yukon (Wilson et al., 2019), the RW, DBI and MXD data were detrended using an age dependent spline (Melvin et al., 2007) within the signal-free framework (Melvin and Briffa, 2008), while constraining the outermost sections of the fitted function to be non-increasing. This approach appears optimal when compared to commonly used data adaptive methods (i.e. negative exponential or linear functions) and greatly reduces the loss of common mid-frequency variability and any potential warming signal expressed in the tree ring series (Wilson et al., 2019). Chronology signal strength was assessed using the mean-interseries correlation (RBAR) of the detrended series while between-parameter chronology coherence was assessed using correlation matrices and principal component analysis (PCA) over the common 1783–2004 period where replication was greater than 10 series.

The climate signal expressed by the RW, DBI and MXD data was examined by calculating monthly and seasonal correlations between the individual chronologies and a regional grid ($0-2$ °E/$42-43$ °N) of CRUTS4.02 mean temperatures (Fig. 1 – Harris et al., 2014). The temporal stability of the strongest relationships between the tree-ring variable chronologies and seasonal mean temperatures was explored using running 31-year Pearson correlations.

Finally, a superposed epoch analysis (SEA) was performed on all the parameter chronologies using the most extreme low index (< -2 STDEV) value years consistent to all three MXD chronologies. These years are inferred to represent the coldest summers over the last 200+ years and the SEA will allow the assessment of not only the likely minimal and lagged response in the RW data (Franke et al., 2013; Lücke et al., 2019), but also how well the DBI data express these cold summers. For the SEA, the 15 years after each identified cold year are transformed to z-scores with respect to the mean and standard deviation of the preceding 5 years and the varying epoch segments averaged to derive a mean change in z-score values.

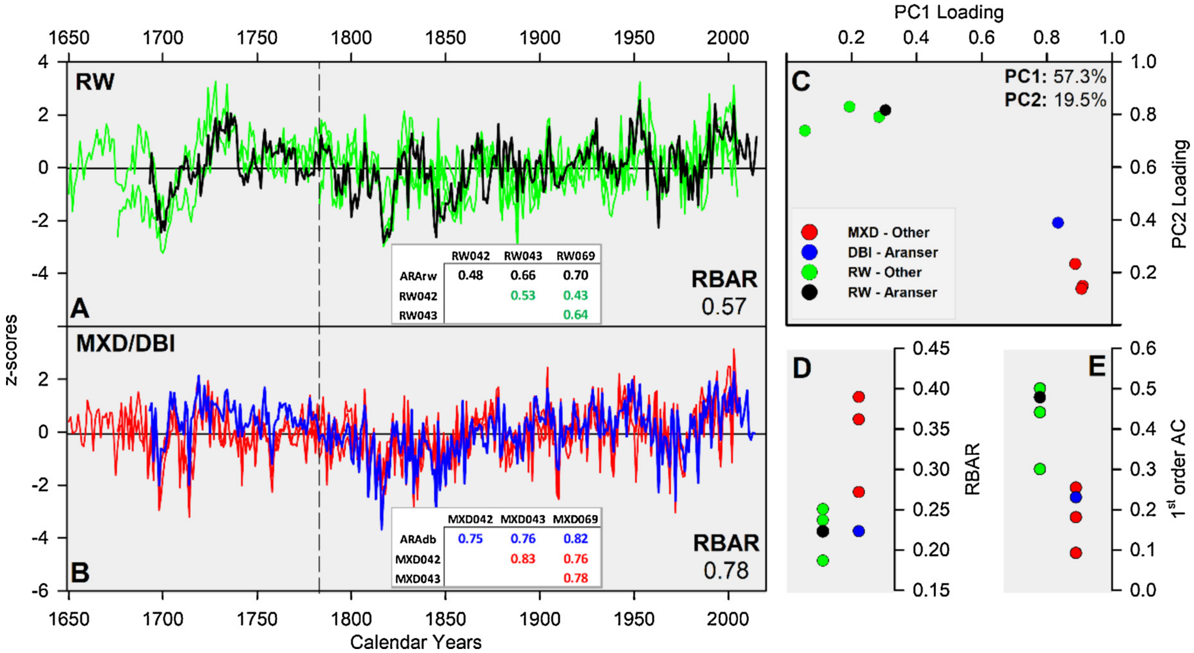
3. Results and discussion

The between-chronology coherence is stronger for MXD/DBI than RW with a mean inter-series correlation of 0.78 compared to 0.57 (Fig. 2A and B). The Aranser RW chronology correlates with the other sites with a range of 0.48–0.70 (mean $r = 0.61$), while the DBI data express a range of 0.75 – 0.82 (mean $r = 0.77$) with the MXD data. This



Site	ITRDB Code	Latitude	Longitude	Elevation (masl)	TR Parameters	Full Period
Eyne	Fran042	42°28'0.00"N	2° 7'2.00"E	2400	RW/MXD	1736-2004
Lac d'Aumer	Fran043	42°51'0.00"N	0° 9'0.00"E	2400	RW/MXD	1324-2005
Port de Cabus	Spai069	42°32'38.78"N	1°25'1.38"E	2450	RW/MXD	1377-2005
Aranser	na	42°27'20.89"N	1°36'6.44"E	2380	RW/DBI	1546-2015

Fig. 1. Upper: Location map of the study site (Aranser) in relation to nearest three test sites from the International Tree-Ring Databank (ITRDB) that have both RW and MXD data. Inset table details ITRDB code, location, elevation, parameters measured and full period coverage for each site. RW = ring-width, MXD = maximum latewood density and DBI = delta blue intensity. The grey box denotes the regional grid (0–2 °E/42–43°N) of the CRUTS4.02 used for climate analyses. **Lower:** Three example core scans showing the different degrees of colour change. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



	RW042	RW043	RW069
ARArw	0.48	0.66	0.70
RW042		0.53	0.43
RW043			0.64

	MXD042	MXD043	MXD069
ARAdb	0.75	0.76	0.82
MXD042		0.83	0.76
MXD043			0.78

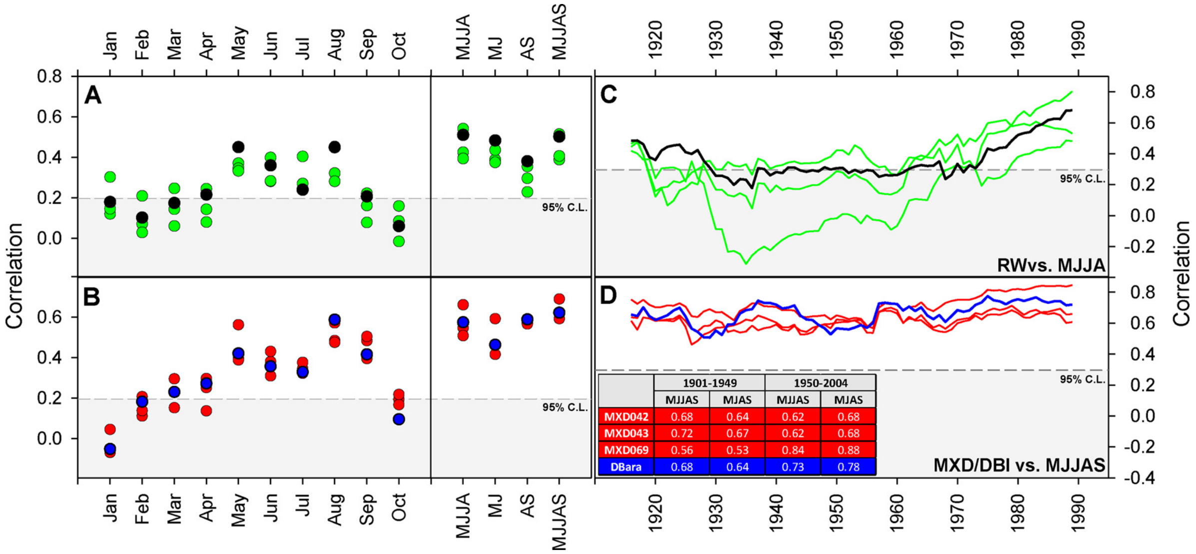
Fig. 2. Comparison of Aranser RW (black) and DBI (blue) chronologies (including correlation matrices − 1783–2004 and mean-interseries correlation values (RBAR)) with appropriate RW (A, green) and MXD (B, red) data from the other three sites. The time-series represent age-dependent spline (with signal free) detrended chronologies transformed to *z*-scores over the 1783–2004 common period (denoted by vertical dashed line); (C) Scatter plot of Principal Component Analysis loadings of each chronology on the first two eigenvectors including explained variance on each PC. Legend denotes consistent colour scheme used for all figures; (D) mean inter-series correlations (RBAR) of all possible bivariate combinations between the detrended tree series for each site chronology; (E) mean 1st-order order autocorrelation values for chronology time-series in (A) and (B) calculated over the 1901–2004 period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stronger common signal of the MXD/DBI data is further highlighted by the PCA with the MXD/DBI chronologies loading on PC1 (explaining 57.3% of the overall variance) while the RW data load on PC2 (explaining just 19.5% of the variance – Fig. 2 C). These results clearly highlight the "purer" common signal expressed by the MXD/DBI chronologies compared to RW, which is presumably more influenced by site specific varying ecological factors (Björklund et al., 2014; Rydval et al., 2014, 2018; Wilson et al., 2014, 2017a). Importantly, the DBI data express a very similar signal to the MXD data and qualitatively, despite the discolouration issues noted in some samples (Fig. 1), the DBI chronology does not deviate in any significant way from the MXD series (Fig. 2B).

The chronology signal strength, measured by the mean inter-series correlation (RBAR), is weaker for the RW data (0.23 ± 0.03 STDEV) than MXD (0.34 ± 0.06 STDEV). Previous studies have detailed the weaker signal strength in BI-based parameters compared to MXD (Rydval et al., 2014; Kaczka et al., 2018; Wilson et al., 2014, 2017a) and our results are no different, with DBI expressing similar signal strength properties to RW (RBAR = 0.23 – Fig. 2D). The implications of these results are that on average, for MXD data, ca. 11 trees are needed to attain an Expressed Population Signal of 0.85 (Wigley et al., 1984; Wilson and Elling, 2004) while ca. 19 trees are needed for RW and DBI.

Despite the RW and MXD/DBI data expressing enough unique variance to identify two eigenvectors in the PCA (Fig. 2C), the correlations of the RW and MXD/DBI chronologies with mean monthly and seasonal temperature are broadly similar (Fig. 3) although RW expresses an overall weaker climate signal. Over the 1901–2004 period, the RW data for all 4 sites correlate most strongly with May-August temperatures with a range of 0.42 – 0.54 (Fig. 3A). For MXD, correlations are highest with May-September temperatures – the range being 0.59–0.69, while DBI correlates at 0.62 (Fig. 3B). The temporal stability of the climate signal in the RW data is poor (Fig. 3C) with highest correlations noted in recent decades, but most of the RW sites hover around or below significance for most of the 20th century, although one (SPAI069) notably drops to negative values through this period. The climate/parameter relationship of the MXD and DBI data is much more stable, although, as noted by Büntgen et al. (2017), post 1950 correlations are marginally - but not significantly - stronger (Fig. 3D). Büntgen et al. (2017) calibrated against a split season of May–June and August–September and attained a correlation of 0.72 over the 1950 – 2014 period. In our analyses herein, all chronology correlations with July temperatures for both RW and MXD/DBI are significant (Fig. 3A and B) and we see no justification for the use of the split season. Correlations with the full May-September season are in fact more temporally stable, with the MXD data for the 1901–1949 and 1950 – 2004 periods expressing a mean correlation of 0.65 (± 0.08 STDEV) and 0.69 ((± 0.12 STDEV), respectively (see inset table in Fig. 3D). At the individual site level, FRAN042 and FRAN043 actually express marginally stronger correlations for the earlier period. The DBI chronology correlates at 0.68 and 0.73 for both periods. For the split May–June/August–September season, the equivalent correlations for MXD and DBI are 0.61 (± 0.07 STDEV) and 0.65 (± 0.11 STDEV), and 0.64 and 0.78. However, regardless of which season is deemed appropriate, the DBI results are not significantly different to those of the MXD data.

As the Aranser trees and those from the other three sites were sampled near upper treeline, the positive correlations with summer temperatures are not unexpected (Fig. 3). It is well known that MXD expresses a strong correlation with summer temperatures and it is the tree-ring parameter of choice if one wants to explore the summer temperature response to significant major volcanic eruptions (Anchukaitis et al., 2012; D'Arrigo et al., 2013; Schneider et al., 2015). To assess whether DBI may also portray similar properties to MXD, significant inferred cold years were identified using annual values 2 standard deviations below the 1783–2004 mean across all three MXD chronologies. These years – 1809, 1816, 1829, 1835, 1850, 1910, 1939, 1963 and 1972 – were utilised in a Superposed Epoch Analysis (SEA) to identify the mean response of the RW and DBI data to extreme inferred cold summers. Three of these years (1809, 1816 and 1835) are well known cool summers related to major tropical eruptions (Wilson et al., 2016). The SEA results (Fig. 4) show that the DBI data express the same mean response cooling of ca. 2 standard deviations as the MXD sites. The RW chronologies, on the other hand, show a complex, more dampened decrease of only ca. 1 standard deviation one year later than the MXD/DBI data. SEA analyses comparing RW and MXD at regional and hemispheric scales show similar differences between the two parameters (Anchukaitis et al., 2012; D'Arrigo et al., 2013; Wilson et al., 2016). Measurements of 1st order autocorrelation (AC) are often used to highlight potential autoregressive biological memory issues of RW when compared to MXD (Franke et al., 2013; Lücke et al., 2019). The mean 1st order AC of the four RW chronologies (1901–2004) is



	1901-1949		1950-2004	
	MJJAS	MJAS	MJJAS	MJAS
MXD042	0.68	0.64	0.62	0.68
MXD043	0.72	0.67	0.62	0.68
MXD069	0.56	0.53	0.84	0.88
DBara	0.68	0.64	0.73	0.78

Fig. 3. Correlation response function analysis results (1901–2004) between RW (A) and MXD and DBI (B) ADSsf chronologies and monthly and seasonal CRUTS4.02 mean temperature data. (C) and (D) present running 31-year Pearson correlations for RW vs. MJJA and MXD/DBI vs. MJJAS over the same period. 95% confidence limits (CL) are shown for both sets of analyses. The embedded table show correlations between each MXD DBI chronology with May–September and May–June and August–September seasons for the 1901–1949 and 1950–2004 periods.

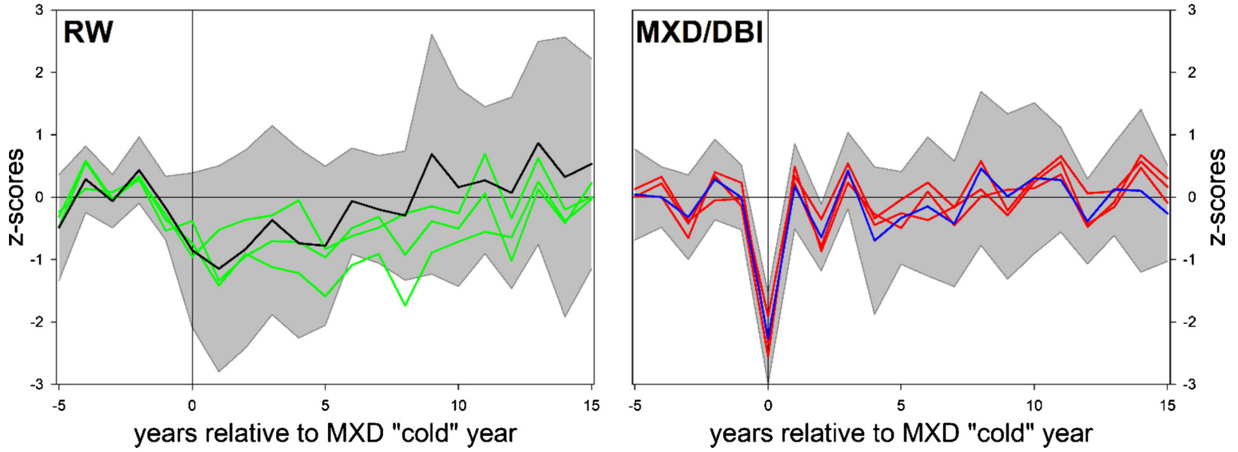


Fig. 4. Superposed Epoch Analysis for the individual RW and MXD/DBI chronologies for the inferred coldest years (< −2 STDEV below 1883–2004 mean) for all three MXD chronologies (Fig. 2B). These years are 1809, 1816, 1829, 1835, 1850, 1910, 1939, 1963 and 1972. The 2-sigma error for the Aranser RW and DBI data are shown with grey shading.

0.44 (± 0.09 STDEV – Fig. 2E) while for the MXD data it is 0.18 (± 0.08 STDEV). The DBI data again sit within this MXD range with a mean 1st order AC of 0.24. Initially, these results would sit well with the SEA results in that the RW data express a dampened lagged response. However, the 1st order AC for both the MJJA and MJJAS mean temperature seasons is 0.36 suggesting that caution is needed in assuming that ring density parameters reflect the spectral properties of the instrumental data, as they may in fact be too white.

4. Concluding remarks

In this study, we have measured DBI data from a single well replicated *P. uncinata* site at upper treeline in the Spanish Pyrenees and compared the chronology properties with MXD data from similar sites within 120 kms. Despite heartwood/sapwood and fungal-related discolouration (Fig. 1), the DBI data appear to minimise the colour biases that would be expressed by the latewood BI data, and no significant trend differences are noted between the MXD and DBI chronologies (Fig. 2B). Principal component analysis, correlation response function analysis and Superposed Epoch Analysis show definitively that the DBI data are indistinguishable to the MXD data and that DBI expresses a similarly “pure” climate signal as MXD when compared to their RW counterparts (Björklund et al., 2014; Rydval et al., 2014, 2018; Wilson et al., 2014, 2017a). In many respects, these results are not surprising as both DBI and MXD measure similar wood properties – the relative density of the latewood of conifers. However, the number of studies utilising DBI are still small (Björklund et al., 2014, 2015; Wilson et al., 2017b) and it cannot be guaranteed that this parameter will always minimise discolouration bias. The only property of the DBI data significantly different to MXD was the chronology signal strength (RBAR) where the DBI data express a weaker between-tree common signal and behave more like RW data with ca. 19 trees being needed to attain an EPS value > 0.85 (Fig. 2D). As the generation of latewood BI or DBI data is so much cheaper than MXD, this limitation is not deemed to be a serious issue.

This paper represents the latest of only a small number of studies (Björklund et al., 2014, 2015; Wilson et al., 2017b) examining the potential of DBI for dendroclimatology. Our results, despite utilising data from only one location, strongly suggest that the added expense of measuring MXD data is likely not needed in this region and substantial improvement in calibration and validation would be gained by expanding the *pinus* DBI network across the Pyrenees region (see Linán et al., 2012) rather than focussing on a single location with very high replication (Büntgen et al., 2017). 30–40 living trees would be adequate for each site, but for the period prior to 1700, preserved non-living snag, sub-fossil or historical (Wilson et al., 2004) material would be needed to significantly extend the chronologies back in time. Sites with profuse amounts of surface dead snag material (Büntgen et al., 2017) would be vital, as well as exploring the potential of finding high elevation lakes where stem material may be preserved in the near-shore sediments. However, the darker nature of preserved dead surface or sub-fossil wood could be a major hinderance, due to the discolouration bias, for the use of reflectance-based parameters for dendroclimatology. Some studies have overcome these colour biases effectively by either adjusting the BI data using contrast adjustments (Björklund et al., 2015; Fuentes et al., 2018) or employing a band-pass approach where the low frequency signal is derived from the RW data and the high frequency is driven by the BI data (Rydval et al., 2017). Much more experimentation is needed, however, before the utilisation of BI and related parameters, measured from preserved snag, sub-fossil or historical material, can be deemed as trustworthy. It’s not inconceivable that wood anatomical approaches may, in the end, provide the true non-biased estimate of relative wood density in tree-ring series (Björklund et al., 2020).

Acknowledgements

This paper is dedicated to Fritz Schweingruber who passed away while this manuscript was being finalised. He was an inspiration to all dendrochronologists and was integral in the exploration of conifer tree-ring density parameters for dendroclimatology in the 1970s. The development of blue intensity over the last decade benefitted greatly from Fritz’ experience and insight. He will be sorely missed. Many thanks to Cheryl Wood and Hannah Frith for measurement of much of the material utilised in this study and Jesper Björklund for his kind but robust review.

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