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Different maximum latewood density and blue intensity measurements techniques reveal similar results

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ABSTRACT

Annually resolved and absolutely dated Maximum Latewood Density (MXD) and Blue Intensity (BI) measurements are frequently used for reconstructing summer temperature variability over the last centuries to millennia. A direct comparison of the outcome of both methods using similar material is needed due to how quickly this method is being adopted. The application of slightly different measuring systems (hardware) and analysis tools (software) in tandem with different wood samples and preparation procedures further challenges any straightforward assessment. Here we process 26 Norway spruce samples from the upper timberline in the Polish Tatra Mountains with the six most frequently used MXD and BI applications. Although offset is found in the raw MXD and BI data (0.04–0.13 g/cm^3 and 0.45–1.58 dimensionless blue intensity), interannual and longer-term fluctuations are significantly ($p < 0.01$) positively correlated between all MXD and BI time-series. Our results emphasize the potential of faster and cheaper, as well as overall more user-friendly techniques to generate reliable MXD surrogates for high-frequency dendroclimatological studies. Although the correlations between MXD and BI were lower than within MXD and BI, the results of growth-climate response performed for both proxies show only marginal differences. The obtained level-offset further questions the suitability of joining different density surrogates for developing long-term composite chronologies to reconstruct low-frequency climate variability.

1. Introduction

Maximum Wood Density, MXD is recognized as one of the strongest and most robust tree-ring proxies of summer temperature in northern and high elevation environments. It is widely used for local (Sander et al., 1995; Büntgen et al., 2007; Gunnarson et al., 2011), regional (Barber et al., 2004; Wiles et al., 2014; Esper et al., 2014) and hemispheric (Briffa, 2000; Briffa et al., 2001; Breitenmoser et al., 2012; Wilson et al., 2016) tree ring studies and several reconstructions of millennial climate variability (Luckman and Wilson, 2005; Büntgen et al., 2006; Esper et al., 2012; Melvin et al., 2013; Zhang et al., 2015). Several techniques of measuring wood density exist including the use of different kind of rays (beta rays, Cameron et al., 1959; X-rays, Polge, 1970; Schweingruber et al., 1978; gamma rays, Woods and Lawhon, 1974), electric properties of the wood (high-frequency densitometry, Schinker et al., 2003), optical features of the wood surface (reflectance of the different spectrum of visible light, Sheppard et al., 1996), mechanical resistance against probing drill (Rinn et al., 1996), and neutron imaging (Lehmann et al., 2001). Although the new techniques allow making 3D (Van den Bulcke et al., 2014) and intra-annual (Bouriaud et al., 2005, Babst et al., 2016) analyses, annual MXD is so far the most common application of the different wood density parameters. Historically and currently (Jacquin et al., 2017) various X-ray techniques are the main tool employed to measure wood density. To obtain MXD-values a thin wood sample of a specified thickness, usually 1.2 mm, is X-rayed. The transmitted radiation is recorded with a film, or digital X-ray camera and the resulting radiographic image analyzed for its grey scale intensity variations between and within tree-rings using the simple relationship between material density and attenuation of the X-ray-radiation. To obtain absolute density values a calibration wedge with steps of known thickness of a homogenous material with known material density (usually acetate or acrylic) is additionally X-rayed with a

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sample and later used to calibrate the grey scale (light) intensity of the sample radiographic image to absolute density values (in g/cm^3) using the formula:

Wood density = Calibration Material Density * Step Thickness/ Wood sample thickness.

Several types of X-ray devices are currently used (Jacquin et al., 2017), probably most common are the Walesch system from Walesch electronics GmbH (Eschbach et al., 1995) using analogue film material and the ITRAX Multiscanner from Cox Analytics, Sweden, producing digital images.

However, the persistent development of digital image analyses technology created an opportunity to establish Blue Intensity (BI) as a complement to MXD, but far easier and cheaper to obtained proxy (Sheppard et al., 1996; McCarroll et al., 2002; Campbell et al., 2007, 2011, Björklund et al., 2014,2015).

The basic idea of BI is to measure the intensity of the blue channel of light reflected from the wood surface. The BI value depends on the optical features of the wood, which according to McCarroll et al. (2002) and Campbell et al. (2007) are related to the lignin content of latewood cell walls. Several experimental studies proved a very strong relationship between BI and MXD therefore the Blue Intensity almost from the beginning is known as a so-called "surrogate" for X-ray densitometry (McCarroll et al., 2002; Campbell et al., 2007, 2011; Rydval et al., 2014; Björklund et al., 2014; Björklund et al., 2015). The blue light measured from the RGB spectrum in digital images of adequately prepared wood surfaces using digital image analysis software has become a standard methodology (e.g., Campbell et al., 2011; Rydval et al., 2014). The BI method has been used to extract climatic signals from tree rings and to build multi-century temperature reconstructions (McCarroll et al., 2013; Wilson et al., 2014; Björklund et al., 2015; Dolgova, 2016; Fuentes et al., 2018). The usability of the proxy has been continuously improved, e.g., the initial employment of reflected light (thus the name Blue Reflectance in early publications, e.g., McCarroll et al., 2002) was replaced by absorbed light intensity to ease the comparison with MXD (Rydval et al., 2014). The application of delta BI, i.e. the difference between earlywood- and latewood- blue intensity, now facilitates the analysis of historical and dead wood (Björklund et al., 2014,2015; Wilson et al., 2017) and different techniques of wood preparation and image acquisition were explored (Rydval et al., 2014; Österreicher et al., 2015). Today, several types of hard- and software are used for generating MXD and BI measurements, which are commonly considered in dendroclimatology and dendroecology to develop robust chronology and ultimately reconstruct climatic and environmental signals over various spatiotemporal scales.

Here, we test and compare the main techniques of MXD and BI acquisition using exactly the same physical wood samples (Fig. 1) for every analysis to device cross-comparisons between different software and hardware set-ups.

2. Material and methods

For our comparison, we used material initially sampled to build a network of tree-ring chronologies in the Tatras region, Poland (Büntgen et al., 2007; ITRDB: file DolinaSuchejwody). All increment cores were collected in the autumn of 2004 in the Dolina Suchej Wody Valley, Polish Tatra Mountains, at an elevation of 1480 m a.s.l., near the natural timberline (site location: N49.25°, E20.03°). The stand represents typical Carpathians subalpine forests predominated by Norway spruce (*Picea abies* (L.) Karst). The mean annual temperature at this elevation reaches +2.5 °C, and total annual precipitation sums up to1660 mm (Hala Gąsienicowa meteostation, 1520 m a.s.l., AD 1946-2004).

For this test, 26 samples were randomly selected from the available set of 58 cores; only one core per tree was permitted in the new collection.

Selected cores were prepared for MXD measurements applying the classical method described by Schweingruber (1988, 1996). The 5 mm diameter cores were cut with a high precision twin-blad saw DendroCut (Walesch Electronic, Switzerland) to produce 1.25 mm thick wooden laths. The orientation of tracheids was carefully checked under the microscope to ensure the vertical position of cells in the prepared laths. This step required the splitting of the cores in several (here, from 1 up to 13) pieces. The samples were labeled and stored under constant and controlled climate conditions prior to analysis.

First, an analogue X-ray image of the samples was produced in a climate controlled room (20 °C, 50% relative humidity) at the Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland (WSL). The samples were under X-ray exposure for 70 min with 12 kV/17 mA using a Balteaugraph X-ray generator, and the image was captured on fine-grained film paper (Kodak Industrex). Finally, a Walesch Dendro 2003 densitometry workstation was used to produce and measure wood density based on the analogue X-ray images (Eschbach et al., 1995). A mutli stepped calibration wedge made out of cellulose acetate with known material density and step depths simultaneously X-rayed. In the last step, an empirically derived calibration factor of 0.886 was applied to scale the grey level to gravimetric densities (Lenz et al., 1976; Schweingruber, 1988). The step resolution of the Walesch system is given by a measuring sensor width of 0.5 mm. As the grey level measurement profiles are captured with a 50 time magnification the actual measurement will therefore result in a 10 μm step resolution. The measurements were performed in 2004 whereas the rest of the MXD and BI analyses were conducted between 2013 and 2016.

Exactly the same physical wood samples (laths) were later measured under similar conditions of temperature and relative humidity (20 °C, 50% RH) using an ITRAX Multiscanner, located at the laboratory DendroGreif, University of Greifswald, Germany. This device is based on a 1.9 kW concentrate X-ray emitter in combination with a high-resolution digital radiographic camera and allows scanning wood laths with an optical resolution down to 10 μm in the radial direction. In contrast to the Walesch procedure where the sample is fixed while X-rayed, here the sample is moved in a holder between the X-ray source and digital camera detector with a minimum step-width of 10 μm. This always keeps the X-ray beam axis perpendicular to the sample surface. The X-ray source was operated at 30 KV and 50 mA with an exposure time of 25 ms per point (step). Along with the samples, a calibration wedge of 11 steps of increasing thickness (0, 0.25 mm, 0.5 mm,…., 2.5 mm) is X-rayed and later used for gray scale calibration of the digital images to radiographic wood-densities. For the ITRAX-system there is no empirical scaling factor available for Norway spruce so − in contrast to the Walesch measurements – here X-ray densities are not scaled to gravimetric densities. The digital images of samples and reference are stored and can be measured with any available image analysis software. As the standard procedure, the program WinDENDRO2012b (Regent Instruments, Canada) is applied. In WinDENDRO after the creation of a calibration curve of light intensity using the radiographic image of the calibration wedge, first, a path is manually created on the radiographic image of the sample to determine where density analysis is performed. In a second step ring-and earlywood/latewood boundaries are set in the path following the orientation of the rings. Out of the continuous density profile, WinDENDRO automatically calculates minimum, mean and maximum density for each ring, separately for early- and latewood using the pre-defined calibration curve.

In addition, we tested the CooRecorder 8.0 software (Cybis Electronics, Sweden) on the same ITRAX Multiscanner sample and reference scans. Similarly like in WinDENDRO, first a greyscale calibration using the calibration wedge image as a target is performed. In contrast to WinDENDRO, the measurement is not done along a path, but ring- and earlywood/latewood boundaries are defined with points following a line rectangular to the rings. Light intensity is picked by