

Benchmarking Blue Intensity from drought limited *Pinus sylvestris* using tree-ring anatomy

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ABSTRACT

Robust, high-resolution proxy information on hydroclimate is critical for understanding the recent European drying in the context of natural variability. This is particularly true for Fennoscandia and the surrounding northern high latitude regions, where such records are scarce, and little is known about the physical drivers of these rare events. Recently, the potential of tree-ring Blue Intensity (BI) of *Pinus sylvestris* L. from cool drought-prone sites has emerged as a source of high-resolution hydroclimate information. Limitations to these proxies may however be linked to the analytical measurement resolution of the technique as well as potential color-related biases caused by the heartwood-sapwood transition and decay-associated discoloration of the tree-ring samples. These proxy uncertainties need to be addressed before the methodology can be used more systematically in the context of hydroclimate reconstructions. Here, we evaluate the reliability of BI tree-ring parameters, specifically regarding their ability to accurately track both low-frequency variations as well as hydroclimate extremes. This is accomplished by benchmarking these parameters against newly developed quantitative wood anatomical (QWA) data from *Pinus sylvestris* trees in southeast of Sweden. The ΔBI parameter shows a high similarity to its QWA analogue across scales ranging from interannual to centennial, suggesting that the Δ conversion efficiently overcomes the long-term trend biases seen in the raw BI data. The earlywood and latewood BI parameters record largely the same strong spring-summer precipitation signal, together explaining over 50 % of the variance in May-July precipitation, as do their QWA counterparts. However, both BI and QWA show a pronounced asymmetric response to precipitation extremes such that dry extremes are captured better than the wet extremes. This dry-biased extreme value capture needs careful consideration in future reconstruction efforts. We conclude that tree-ring BI holds significant potential for contributing to regional reconstructions, especially given the untapped opportunities to utilize the region's extensive collection of historical pine material for paleoclimate research.

1. Introduction

Microdensitometric data from tree rings have proven valuable for reconstructing past temperatures (e.g., Wilson et al., 2016). However, much less is known about the potential for reconstructing hydroclimate using alternative tree-ring parameters beyond ring width. Given the scarcity of hydroclimate predictors from high-latitude regions (Linderholm et al., 2018), it is imperative to prioritize research that explores both new and traditional tree-ring proxy parameters in these areas. In Fennoscandia, although the overall climate tends to be humid and cold, certain micro-site conditions, such as well-drained soils, can

lead to substantial moisture limitations for trees. These conditions often result in marginal tree populations that are particularly well-suited for hydroclimate reconstructions. Over the past decades, dendrochronological work has systematically investigated the use of tree-ring data from such sites for drought reconstructions at various regional and spatial scales (Jönsson and Nilsson, 2009; Linderholm and Molin, 2005; Seftigen, Björklund, et al., 2015; Seftigen, Cook, et al., 2015; Seftigen et al., 2017; Seftigen et al., 2013). For example, in southeastern Sweden, recent studies have demonstrated strong connections between latewood density measured using X-ray (Rocha et al., 2020) or Blue Intensity (BI) techniques (Seftigen et al., 2020) and growing season hydroclimate.

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However, the applicability of the more cost-effective BI proxy technique over longer timescales and for extreme events remains largely unexplored. This research gap is particularly relevant given the considerable amount of historical tree-ring material available in this region, including building timber that could extend living-tree chronologies back several centuries, potentially even to the Middle Ages (Bråthen, 1995).

Studies using BI data with various species from across a range of sites have demonstrated that BI is prone to bias at lower frequencies, spanning decades to centuries (Björklund et al., 2014; Björklund et al., 2015; Buckley et al., 2018; Rydval et al., 2024; Rydval et al., 2014; Seftigen et al., 2020). To understand this issue, it is important to recognize what BI represents. It represents the proportion of cell wall dimensions relative to the lumen voids, making it analogous to X-ray-based wood density (Björklund et al., 2021). Adhering to this interpretation we will henceforth use “2024 BI standard terminology” proposed in Björklund et al. (2024). The difference between BI and density, and thus the source of bias, arises from the potential distortion of the BI/density relationship due to discoloration of cell walls, which may occur between heartwood and sapwood (Björklund et al., 2014; Buckley et al., 2018; Rydval et al., 2014) or through oxidation processes (Wang et al., 2020). Conversely, it has been suggested that maximum latewood density (MXD) data obtained from X-ray technologies may be subject to a related bias that may not be observed in BI. For instance, MXD values appear anomalously low when examining data from several millennia ago, in contrast to latewood BI measurements (LWBI) (Helama et al., 2022), challenging views that mid-Holocene climate was warmer than 20th century climate (Kaufman and Broadman, 2023). Similarly, Klesse et al. (2025) observed a comparable pattern when comparing MXD data from millennia-old wood with corresponding wood anatomical data. In their study, the discrepancy was most likely due to diffuse depolymerization of cell walls in the dead wood. This process can alter the chemical structure of cell walls without visibly changing their dimensions, thereby biasing X-ray-based density measurements like MXD, while leaving wood anatomical and likely BI data unaffected.

Given the complications with cell wall discoloration and diffuse depolymerization, interpretation of climatic trends from BI or MXD data over centuries and millennia should be approached with caution. This is why the reliability of BI data is most appropriately evaluated through comparison with quantitative wood anatomy (QWA) in tree rings (here referred to as *tree-ring anatomy*), which directly measures cell dimensions. While this technique remains resource-intensive and time-consuming, tree-ring anatomy has the advantage over X-ray-based data in that it exclusively focuses on cell dimensions, thereby isolating the biasing effects of cell wall discoloration on BI data.

A second issue that has received less attention is the ability of BI techniques to capture high and low extreme values. Recently, BI has been reinvented through high-resolution imaging (e.g., Rydval et al., 2024), largely due to the challenges associated with accurately analyzing BI or X-ray density in narrower latewoods (Björklund et al., 2019; Jacquin et al., 2017; Seftigen et al., 2022). Traditional BI typically uses scanned images with a resolution ranging from 1200 to 2400 dpi (Björklund et al., 2019; Kaczka et al., 2018), corresponding to a pixel size of 10–20 microns. To put this into perspective, latewood cells generally have sizes of about 30 microns in the tangential direction and 10 microns in the radial direction. Image resolutions used for BI could thus theoretically be sufficient to properly analyze maximum latewood BI, which typically include 1–2 latewood cells in the radial direction. However, these cells are rarely aligned perfectly along a straight tangential line due to the meandering of ring boundaries. In very narrow latewood bands, there is therefore a considerable risk of including pixels that may belong to the earlywood portions of the current or subsequent ring. Consequently, this inaccuracy can lead to latewood BI-values that consistently underestimate the true latewood density. Although some X-ray techniques provide nominally better precision in selecting latewood cells for latewood parameters, this remains a challenge (Björklund et al., 2019). In contrast, QWA methods allow for precise control over

which cells are included in each annual aggregate (von Arx et al., 2016), reducing the risk of mistakenly incorporating earlywood cells into a latewood parameter. This makes QWA ideal for benchmarking the performance of BI data in estimating dry extremes, especially in cases where narrow rings or latewoods are present. In wider rings, typically associated with positive extremes (i.e. pluvials), the technical challenges of measurement are less critical. However, it is not guaranteed that trees sensitive to drought will respond linearly to excessive soil moisture. This non-linear response has been observed in Sweden (Rocha et al., 2020; Seftigen et al., 2020), and even the most drought-sensitive species, such as the Blue oaks (*Quercus douglasii*) of California, struggle to capture the full range of positive extremes (Belmecheri et al., 2016). Nevertheless, applying QWA techniques to moisture-limited trees at higher latitudes may provide insights that BI and X-ray technology have missed, making the exploration of positive extremes a compelling area of study.

In this work, we build upon the findings of Seftigen et al. (2020) and evaluate the reliability of tree-ring BI from high-latitude regions as a proxy of past hydroclimate conditions. Specifically, we evaluate its ability to accurately track low-frequency variations and extreme events by benchmarking the BI records against newly developed quantitative wood anatomical measurements. We analyze and compare parameter-coherence, variance and persistence, and the nature and strength of the climate response patterns in *Pinus sylvestris* from cool-dry sites in Gotland, southeastern Sweden. We aim for the insights gained through this systematic comparison to inform future research on BI, particularly as the methodology continues to evolve and new sites and species are incorporated into the expanding pool of BI chronologies (Kaczka and Wilson, 2021).

2. Materials and methods

2.1. Tree-ring data

Increment cores were collected from living Scots pine (*Pinus sylvestris*) trees across the northern edge of the Isle of Gotland (18.35° E – 18.90° E, 57.80° N – 57.90° N) in southeastern Sweden (Fig. 1a). Based on data from the Visby airport meteorological station (WMO station code 2590), located approximately 30 km from the sampling area, the region receives an average of 520 mm of precipitation annually (1971–2024). Spring to early summer is the driest period, often receiving less than 30 mm of rainfall per month. Mean monthly temperatures range between –0.8°C and 17°C (1971–2024 period).

The tree-ring sampling took place in plots located in a calcareous flatrock landscape with shallow rendzina-like soils, generally less than 30 cm deep, and a sparse tree canopy primarily dominated by Scots pine (Fig. 1b). The high sun exposure and low soil moisture levels in these stands make them particularly susceptible to drought. The understory vegetation is diverse, including species from forest-rim communities, calcareous shallow-soil communities, meadows, steppe communities, acidophilous pine forests, and alpine Dryas communities (Bjørndalen, 1985). Historically, the forest was used as woodland pasture, although this practice has since ceased, and cores were taken from dominant trees showing no recent signs of cutting or grazing.

For the BI chronology, measurements were made on 24 radii from 21 living trees, covering the period from 1769 to 2017. This chronology was previously part of a larger network, which was utilized in an initial study to investigate the climate signal in BI data from southern Fennoscandia (Seftigen et al., 2020). As with the QWA samples, the tree-ring cores were selected from dry microsites with shallow soils to maximize the moisture signal in tree growth. We focused specifically on middle-aged (~100–200 years old) and young (<100 years old) trees to avoid the extremely narrow rings typically found in older specimens, which can be difficult to distinguish and measure. To prepare the samples, they were refluxed for approximately 24 hours with 99 % ethanol in a Soxhlet apparatus, allowing the ethanol to circulate and remove resins and other extractives from the samples. The samples were then

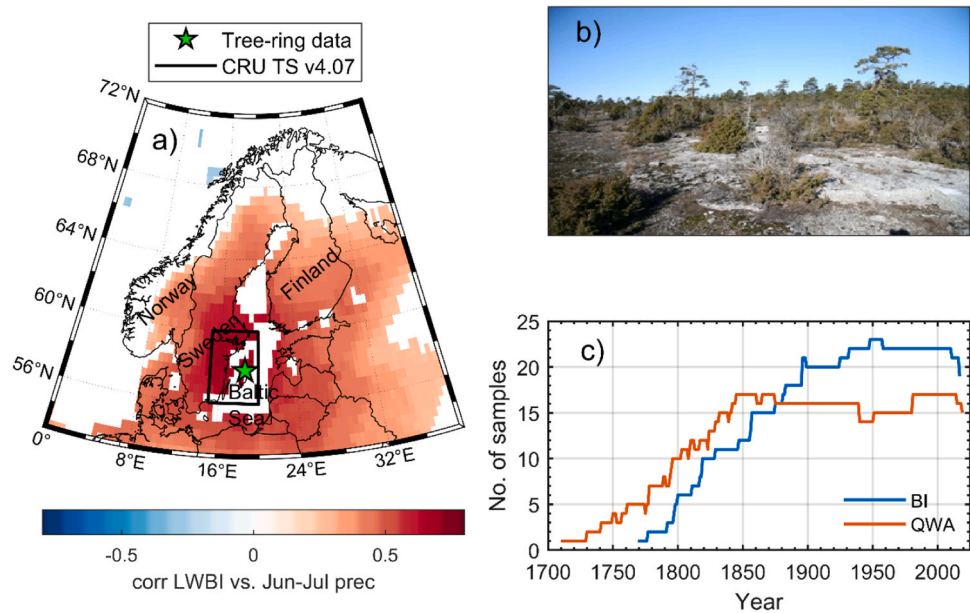


Fig. 1. a) Location of the tree ring sampling site on the isle of Gotland, southeast of Sweden, together with the spatial outline of the CRU TS 4.07 subset (15° - 20° E and 56° - 60° N) used in the climate – growth response analysis. The background shading represents pointwise correlations (significant at $p < 0.01$) between the latewood BI (LWBI) chronology and gridded average June-July precipitation over the 1901 – 2017 period. b) Photo of the study site showing solitary Scots pine trees growing across the drought-prone calcareous flatrock landscape. c) Sample replication through time of the BI and QWA datasets.

glued to core mounts, surfaced using a core microtome (Gärtner and Nievergelt, 2010) and polished with 1200-grit sandpaper, filling cell voids with fine white wood dust to enhance contrast between the cell lumen and walls. BI measurements were performed in the CooRecorder software (version 9.4; Larsson, 2014) on digital images (resolution of 2400 dpi, pixel size ~10 μm) of the tree cores. These images were captured using an Epson Expression 10000XL flatbed scanner and calibrated with SilverFast Ai scanning software and the IT8.7/2 calibration target. The resulting BI data from this study conform to the ‘2024 BI standard terminology’ (Björklund et al., 2024), where measurements are defined as inverted light intensities and thus positively correlated with wood density. Key BI parameters retained for analysis include earlywood BI (EWBI), latewood BI (LWBI), and the derived ΔBI parameter (Björklund et al., 2014), defined as the difference between LWBI and EWBI. For details on the settings used in the CooRecorder program to obtain these measurements, see Table 1.

The QWA measurements were based upon 17 core samples (one radius) from 17 living *Pinus sylvestris* trees, covering the period 1710–2019. These 12 mm cores, sampled in 2020, are distinct from those used for BI measurements, although they were collected from the same forest stands. We argue, nevertheless, that the robust signal strength of the tree-ring parameters of interest and their capacity to adequately represent the population signal with a relatively small sample size allow for a direct comparison between the BI and QWA

chronologies. Additionally, the strong and highly significant correlation ($r = 0.92$, $p < 0.001$, $N = 168$) between first-differenced ring-width chronologies obtained with the BI and QWA techniques, respectively, further demonstrates a high degree of shared signal and supports the rationale for directly comparing parameters obtained with the two techniques. As with the BI sample preparations, each core sample underwent a 24-hour refluxing in 99 % ethanol using a Soxhlet apparatus, followed by embedding in paraffin using the Tissue Processor TP1020 and Histocore Arcadia Embedding Center (Leica, Germany). The samples were then sectioned transversely into 12 μm thick slices using a rotary microtome RM2245 (Leica Biosystems, Germany) equipped with N35 disposable microtome blades (Feather, Japan). These sections were subsequently prepared and stained with a safranin-astrablue solution according to standard procedures (Fonti et al., 2025). High-resolution digital images of each section were captured using a Zeiss Axio Scan Z1 (Carl Zeiss, Germany) at a resolution of 2.3 pixels μm^{-1} and were analyzed using the ROXAS software (v3.1) (Prendin et al., 2017; von Arx and Carrer, 2014), which measured the position and anatomical dimensions of each tracheid cell. For the QWA analysis, the parameters retained included total cell area and cell wall thickness (CWT), with CWT measured in both radial and tangential directions. Maximum and minimum radial CWT were used as analogues for LWBI and EWBI, respectively, in our comparative analysis. Additionally, average CWT was retained to derive anatomical density parameters such as anatomical MXD. Anatomical cell measurements were aggregated in 30 μm -wide bands, subdividing each annual ring parallel to the ring borders. The anatomical density was computed as the ratio of wall area to total cell area within each 30 μm -wide band. To minimize the influence of outliers, values corresponding to the 75th percentile within each band were utilized. For more detailed information on the QWA measurements, refer to Björklund et al. (2020) and Seftigen et al. (2022). The absolute dating of the QWA measurements was facilitated by using a previously obtained ring width chronology as a reference, and subsequently verifying this dating statistically in the program COFECHA (Holmes, 1983). In this manuscript, any mention of ring width specifically refers to the data obtained from the QWA analysis performed in the ROXAS program.

The BI and QWA measurements were processed into chronologies by

Table 1
The frame specification settings used in CooRecorder program (version 9.4; Larsson, 2014) when generating the earlywood BI (EWBI) and latewood BI (LWBI) measurements.

Parameter	w	wLimFact	f	d	k	Select data by:	% of the dark or light wood to use for color data
LWBI	80	10	5	50	0.30	“Mean of sorted pixels”	15
EWBI	80	10	−2	500	0.10	“Mean of slices”	80

simply averaging the raw time series for each parameter. Depending on the type of analysis, our further assessments are either based on raw chronologies, first differenced chronologies, or linearly detrended chronologies (next section). First differencing was applied to the raw tree-ring measurements by subtracting the value for each year (t) from the value of the preceding year ($t-1$). This procedure aimed to isolate annual changes in the data, thereby removing long-term trends, such as those associated with tree age or sample discoloration.

2.2. Data analysis

Descriptive statistics commonly applied in dendrochronology were computed from the tree-ring data, including the average inter-series correlation (Rbar; Wigley et al., 1984) and the first-order autocorrelation coefficient (AR1). Rbar serves as an indicator of the common signal strength for individual parameters, whereas AR1 quantifies the degree of persistence or "biological memory" present in the tree-ring data.

Pearson correlation coefficients were calculated between the tree-ring parameters and monthly meteorological data. The latter were obtained from the CRU TS 4.07 gridded product, using a regional subset averaged over 15°–20° E and 56°–60° N (rectangular box in Fig. 1a). This regional average showed the strongest overall correlation with the tree-ring data (Fig. 1a) and was therefore selected as the calibration target. The climate-growth response analysis was conducted for the period 1901–2017, which was common across all datasets. To minimize the risk of spurious correlations, trends were removed by converting the meteorological and tree-ring series into first differences (Ols et al., 2023).

We applied ordinary least squares (OLS) regression models, including both linear and quadratic forms, to examine linear and potential curvilinear relationships between scaled warm-season precipitation and tree-ring parameters. The scaling ensured that the variables had means of zero and standard deviations of one, allowing for consistent comparison.

The lower frequencies in the LWBI data, defined here as variance over decades to centuries, were assessed through visual comparisons with the corresponding QWA data and by calculating linear trends over the full length of the dataset. Since this study was restricted to living trees, where the timing of the heartwood-sapwood transition occurs approximately synchronously across individuals, the potential to explore variations in the heartwood-sapwood color transition within the current dataset is limited. Consequently, using only living trees makes it difficult to accurately address and eliminate potential age-related differences, such as through regional curve standardization (RCS; Briffa et al., 1992). Since the QWA data does not exhibit heartwood-sapwood differences, any trend deviations between LWBI and its QWA analogue can be attributed to the color transitions and possibly age-related influences. To further disentangle these effects, we applied a Δ -transformation to both BI and QWA data (Björklund et al., 2014). This approach aims to eliminate heartwood-sapwood color differences while preserving age-related effects, allowing a more precise examination of the data through visual assessment and linear trend calculations.

The sensitivity of tree-ring parameters to extremely dry and wet years, defined by the lowest and highest 10th percentiles of warm-season precipitation (CRU TS 4.07 dataset), was further assessed using Superposed Epoch Analysis (SEA) (Haurwitz and Brier, 1981). Key drought years included 1904, 1940, 1941, 1955, 1959, 1967, 1969, 1975, 1976, 1983, 1994, and 2006, while key wet years were 1907, 1910, 1916, 1927, 1960, 1961, 1988, 1998, 2000, 2002, 2009, and 2012. Although 2018 was one of the driest years on record across Gotland and much of Europe (Rousi et al., 2023), it was not included in the SEA, as the BI chronologies extended only through 2017.

To further evaluate the ability of tree-ring parameters to capture high and low extreme values in the target climate variable (based on the 10th percentile threshold), we employed the non-parametric Extreme Value Capture (EVC) test as proposed by McCarroll et al. (2015). The test,

implemented here in the MATLAB environment, allowed us to assess the robustness of tree-ring data in detecting climatic extremes effectively.

3. Results and discussions

3.1. Chronology characteristics

Three different BI parameters, including LWBI, EWBI and the derived Δ BI, were systematically benchmarked against ensembles of ring width and QWA parameters. The BI chronologies span the period from 1769 to 2017, whereas the QWA dataset is 61 year longer, from 1710 to 2019 (Fig. 1c). The Rbar coefficients demonstrated considerable inter-parameter variability, ranging from 0.25 to 0.65 (Fig. 2). Parameters corresponding to the traditional X-ray-based MXD, displayed the strongest common signals (Rbar > 0.55), with the first-differenced LWBI and maximum radial CWT datasets requiring four and three series, respectively, to reach the commonly accepted threshold of 0.85 for the Expressed Population Signal (EPS; Wigley et al., 1984). The higher common signals observed among QWA parameters compared to BI align with results from studies of conifers in temperature-limited regions in Europe (Björklund et al., 2020) and North America (Seftigen et al., 2022). Ring width demonstrated slightly weaker, but still strong, values (Rbar = 0.51), which differs from several previous studies that have shown ring width to have superior signal strength compared to BI (Harley et al., 2021; Rydval et al., 2014; Wiles et al., 2019; Wilson et al., 2021; Wilson et al., 2017; Wilson et al., 2019). Conversely, earlywood parameters such as EWBI, maximum cell area, and minimum radial cell wall thickness, displayed, the weakest statistics (Rbar 0.25–0.39), requiring between 9 (minimum radial CWT) and 17 (EWBI) series to achieve a robust chronology mean. In terms of short-term persistence, the latewood BI and QWA parameters were characterized by little or no autocorrelation (AR1 < 0.1), suggesting a high physiological plasticity and an immediate response to the concurrent environmental stressors at the time of latewood tracheid formation. Notably, the Δ -transformation of the BI data effectively eliminated nearly all autocorrelation, resulting in spectral properties that are closer to white noise than any other parameters studied (Fig. 2).

3.2. Climate-growth response

Despite the overall cold and humid climatological setting of our study region, the pine growth on the calcareous flatrocks is strongly constrained by water availability (Fig. 2). The various tree-ring parameters tested here show distinct and sequential response windows to precipitation in the spring-summer season (May–July), corresponding to the temporal dynamics of environmental constraints affecting cell formation. The overall short window suggests an immediate response to drought, which is expected given the limited water holding capacity of the shallow, stony and highly permeable calcareous substrates characterizing the sampling plots.

The earlywood components - including EWBI, minimum radial CWT and maximum cell area - are all sensitive to May precipitation. Among all 10 tree-ring parameters explored in this study, maximum cell area showed the highest single-month correlations (May, $r = 0.63$). We find that drought stress results in smaller cell lumina, thicker cell walls, and, consequently, higher density in the earlywood band of the ring. Although the precise physiological mechanisms underlying these xylem modifications warrant further investigation and fall outside the scope of the present study, our results suggest that *Pinus sylvestris* growing at our study site has developed an adaptive strategy to withstand increased negative water pressure and mitigate the risks of drought-induced cavitation and embolism under water-limited conditions. This adaptation likely involves a simultaneous downregulation of hydraulic efficiency (i.e. reduced earlywood conduit size) and increased hydraulic safety (i.e. reinforced conduit walls) (Hacke et al., 2015; Hacke et al., 2001). These results reinforce previous findings on hydraulic

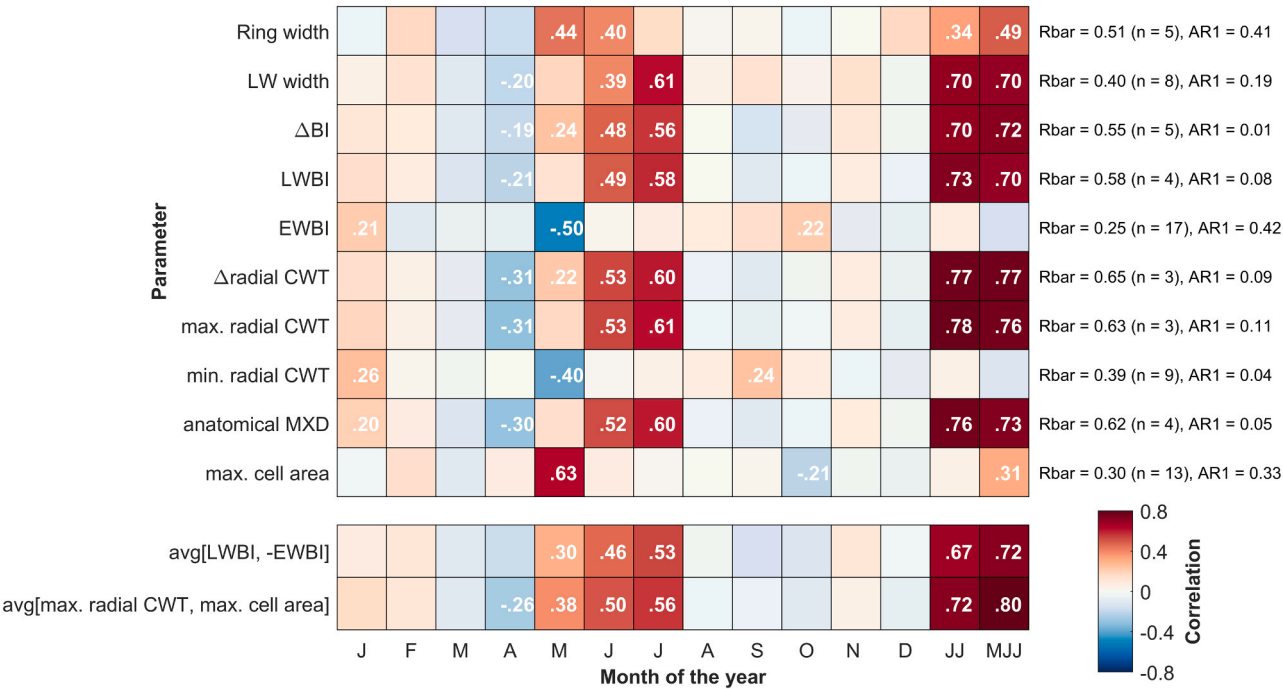


Fig. 2. Pearson's correlations between tree-ring parameters and monthly and seasonally aggregated CRU TS 4.07 precipitation totals over the 1901–2017 period. LW and EW refer to latewood and earlywood, respectively. Numbers in white represent significant ($p < 0.01$) correlations. The Rbar, the number of series (n) needed to attain an EPS threshold of 0.85, and the first order autocorrelation (AR1) statistics for each parameter are provided to the right in the chart. Tree-ring and climate data have been transformed into first differences prior to the growth – climate response analysis and the Rbar computation, whereas the first order autocorrelation is based on linearly detrended data. The bottom two rows display the precipitation responses for z-scored and then averaged indices of latewood BI (LWBI) and inverted earlywood BI (EWBI), along with max. radial CWT and max. cell area.

acclimation in *Pinus sylvestris* (Liang et al., 2013) and in several other conifer species (e.g., Bryukhanova and Fonti, 2012; DeSoto et al., 2011) in arid environments.

Strong positive correlations (ranging from 0.67 to 0.78) are found between June–July average rainfall and the following parameters: LWBI, latewood width, and the latewood QWA parameters (Fig. 2). Among these parameters, the strongest climate sensitivity is noted for maximum radial CWT (JJ, $r = 0.78$). The strength of this climate response is comparable to what has been previously observed in temperature-limited conifers (Björklund et al., 2020; Björklund et al., 2023; Seftigen et al., 2022). LWBI displays a slightly weaker response to June–July rainfall (JJ, $r = 0.73$). These observations suggest that reduced moisture availability towards mid-late summer may inhibit cell wall thickening, thus leading to lower density in the latewood portion of the ring. This effect on anatomical features may reflect carbon shortage resulting from stomatal closure and reduced conductance, which help prevent water loss during dry conditions. We also noted several instances of "blue rings" (Piermattei et al., 2015) in the anatomical structure of rings formed during particularly dry years, such as 2018 (results not shown), which further supports the idea that drought stress may impede lignification in latewood cells. Although no BI measurements were available for this particular year, it is reasonable to assume that the LWBI would have been correspondingly low. However, it is important to note that the final stages of cell development, such as cell wall maturation and lignification processes, typically extend well into summer and even fall (Rossi et al., 2008). In this study, the lack of significant correlations with climate conditions beyond July is somewhat unexpected. In regions where growth is not primarily constrained by temperature, one might reasonably expect that maturation processes could extend later into the growing season, potentially influencing tree-ring parameters well beyond mid-summer. To our knowledge, no studies have investigated cambial activity and xylogenesis in *Pinus sylvestris* growing on calcareous flatrocks, which restricts further exploration of the mechanisms

underlying the absence of a precipitation signal past June–July.

We note that the strength of the climate sensitivity of ΔBI remains fairly stable following the Δ-adjustment, which is not unexpected given that the LWBI and EWBI chronologies correlate poorly with one another at the inter-annual time scales ($r = 0.16$, $p > 0.01$). Rather, by incorporating earlywood information, the Δ-transformation extends the best-fit target season to include May as well (MJJ $r = 0.72$). We obtain similar results by averaging scaled indices (z-scored over the 1901–2017 period) for LWBI and inverted EWBI, as well as for maximum radial CWT and maximum cell area, without weighting the individual proxies at this initial exploratory stage. This approach yields correlations with May–July precipitation of $r = 0.80$ ($R^2 \sim 65\%$) for the QWA parameters and $r = 0.72$ ($R^2 \sim 50\%$) for the BI parameters (see lower panel in Fig. 2). Although integrating climate conditions across a longer seasonal period can offer advantages for future reconstructions, it might also mask significant shorter-duration and season-specific details in the pre-instrumental record. An alternative strategy could be to capitalize on the distinct seasonal moisture signals encoded in the individual earlywood and latewood components, as demonstrated in studies such as those by Griffin et al. (2011), (2013) and Crawford et al. (2015). Such an approach may allow for detailed drought reconstructions at seasonal scales and shed light on potential unusual shifts in moisture patterns between spring and summer, as well as the significant ocean-atmospheric dynamics at play.

3.3. Long-term trends

Given that the BI and the corresponding QWA parameters respond similarly to the same climatic forcing at the inter-annual scale (Fig. 2), it is reasonable to assume that these parameters would also exhibit similar responses to climate variability over longer time scales. However, an analysis of long-term trends reveals a systematic centennial-scale decline in both LWBI and EWBI (Fig. 3a) that is not evident in the two

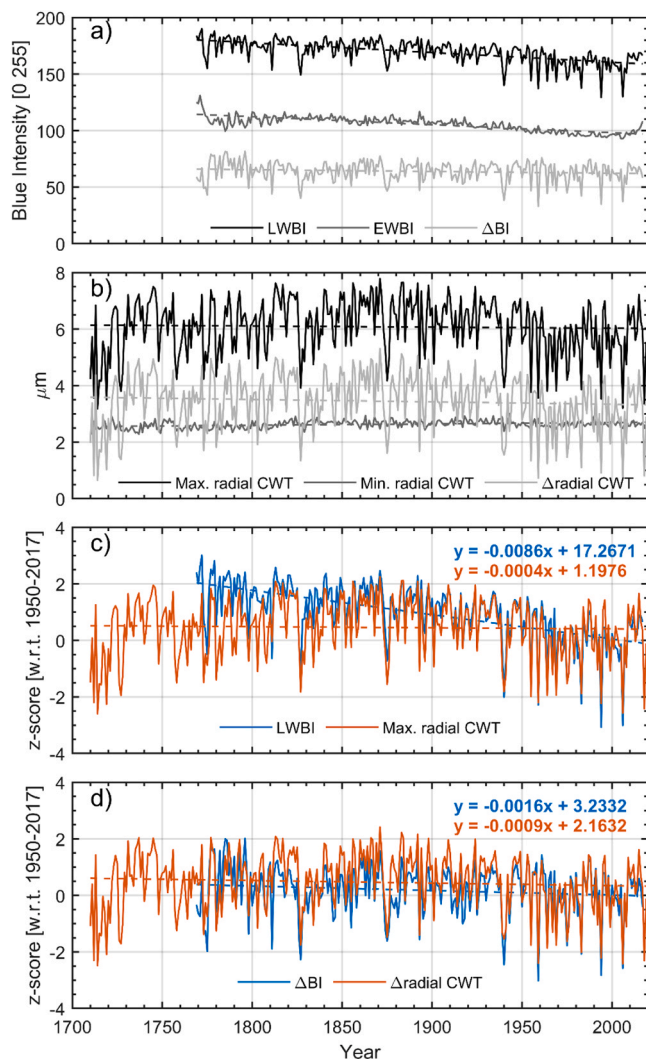


Fig. 3. a) Time series plots of raw unstandardized BI chronologies measured in the latewood (LWBI) and earlywood (EWBI) portions of the ring, along with the ΔBI chronology derived from the former two parameters. b) The QWA counterparts, including max. and min. radial CWT, and the Δradial CWT. c) – d) Linear trend comparison between selected parameters over the common 1901 – 2017 interval. The data have been scaled to have means of zero and standard deviations of one over the 1950 – 2017 period (i.e. z-scores). Note that the long-term negative trend seen in raw LWBI values is largely absent in the ΔBI parameter.

QWA analogues - the maximum and minimum radial CWT (Fig. 3b-c). Converting the BI measurements into ΔBI efficiently removes this long-term trend, resulting in a time series that more closely aligns with the QWA analogue (Fig. 3d). It also aligns with instrumental warm-season precipitation data, which lacks any significant trend over the 1901–2017 period (Fig. 4a). It thus appears that transforming LWBI to ΔBI does not compromise high-frequency (i.e. interannual) precipitation sensitivity (Fig. 2), while maintaining strong low-frequency alignment with both instrumental and QWA counterparts. Hence, the divergence between BI and QWA parameters may be attributed to cell wall discoloration (Björklund et al., 2014), likely due to the color differences between heartwood and sapwood.

For comparison, we also applied a Δ-transformation to the maximum radial CWT by subtracting minimum radial CWT from maximum radial CWT (Fig. 3b). This approach could help alleviate the effects of tilted tracheid angles relative to the transverse surface used for QWA measurements. Non-perpendicular tracheid angles can introduce varying shadow effects in scanned images, potentially obscuring the true shape

and dimensions of the tracheid cells. However, in this case, the low variability in minimum radial CWT results in the derived ΔCWT parameter being largely similar to the maximum radial CWT regarding the long-term trend (Fig. 3b) and climatic signals (Fig. 2). This suggests that minimal variability is typical for earlywood cell wall parameters, and the negative trend observed in EWBI is primarily due to differential discoloration of heartwood and sapwood, which is neutralized by the ΔBI transformation. Any potential effects from age-related differences in the trees and in the QWA and BI parameters are expected to be minor, as both Δ chronologies exhibit similar trends (Fig. 3d), whereas the original (i.e. non-Δ transformed) chronologies diverge (Fig. 3c). If age-related differences between QWA and BI were the primary factor affecting the long-term trends, the Δ-transformation would likely have a minimal impact on the results.

3.4. Capture of extremes

We further assess the extent to which various tree-ring parameters capture warm-season precipitation extremes. Prior dendrochronological studies have documented asymmetries in the relationship between tree growth and hydroclimate extremes (Maxwell et al., 2024), particularly during the cool season in semi-arid regions of the western United States (Dannenberg et al., 2019; Sun et al., 2017; Wise and Dannenberg, 2019). These studies indicate that dry extremes are more effectively captured than wet extremes, resulting in a dry-biased asymmetry. While non-linear growth responses to temperature have been thoroughly studied in Fennoscandia and the rest of Europe (Ljungqvist et al., 2020), the extent to which tree-ring records from Fennoscandian dryland forests demonstrate similar asymmetric responses to hydroclimatic changes remains largely unquantified.

Here, we show that both the ΔBI and max. radial CWT parameters pass the simple non-parametric test for ‘Extreme Value Capture’ (McCarroll et al., 2015) with respect to the 10 % driest warm-season precipitation extremes (Fig. 5a). Out of the 12 recorded driest years, ΔBI captured 10 years and maximum radial CWT 11 years, which is strongly significant ($p < 0.001$). Conversely, for the wet extremes at the 10th percentile threshold, both parameters capture two of the 12 years, which is not statistically significant ($p = 0.2$). This apparent asymmetric extreme capture is further visualized by the SEA (Fig. 4b-c). We find that ΔBI closely tracks precipitation patterns prior to, during and following drought events, as does its QWA counterpart (Fig. 4b). There are no apparent persistence or legacies of drought in the two proxy parameters, but rather an immediate recovery one year after the extreme event. However, in terms of individual years, it appears that ΔBI overestimates some of the drought extremes. This is also apparent from the probability density distributions (Fig. 5b), showing that ΔBI values are negatively skewed towards lower values, whereas the distribution of warm-season precipitation and maximum radial CWT are relatively symmetric. This overestimation may be partially attributed to resolution bias in LWBI measurements (see Björklund et al., 2019), where the lower resolution of BI measurements leads to systematic offsets of density maxima in annual tree-ring profiles towards lower values, particularly pronounced in narrower rings associated with dry years. Regarding the wet extremes, both the SEA (Fig. 4c) and density distribution profiles (Fig. 5b) jointly confirm an underestimation of the actual values by both the ΔBI and its anatomical analogue.

The dry-biased asymmetrical response to precipitation has previously been attributed both to hydrological and physiological mechanisms. Abundant precipitation over short periods may lead to soil saturation and increased runoff, particularly at our sampling sites where thin soil layers and coarse textures contribute to limited water retention capacity. Hence, only a fraction of the precipitation becomes available for growth (Fritts, 2001). In this context we note the possibility that our finding represents some upper threshold for asymmetric growth response to precipitation, since we intentionally sampled trees in locations experiencing high moisture stress. Other mechanisms may involve

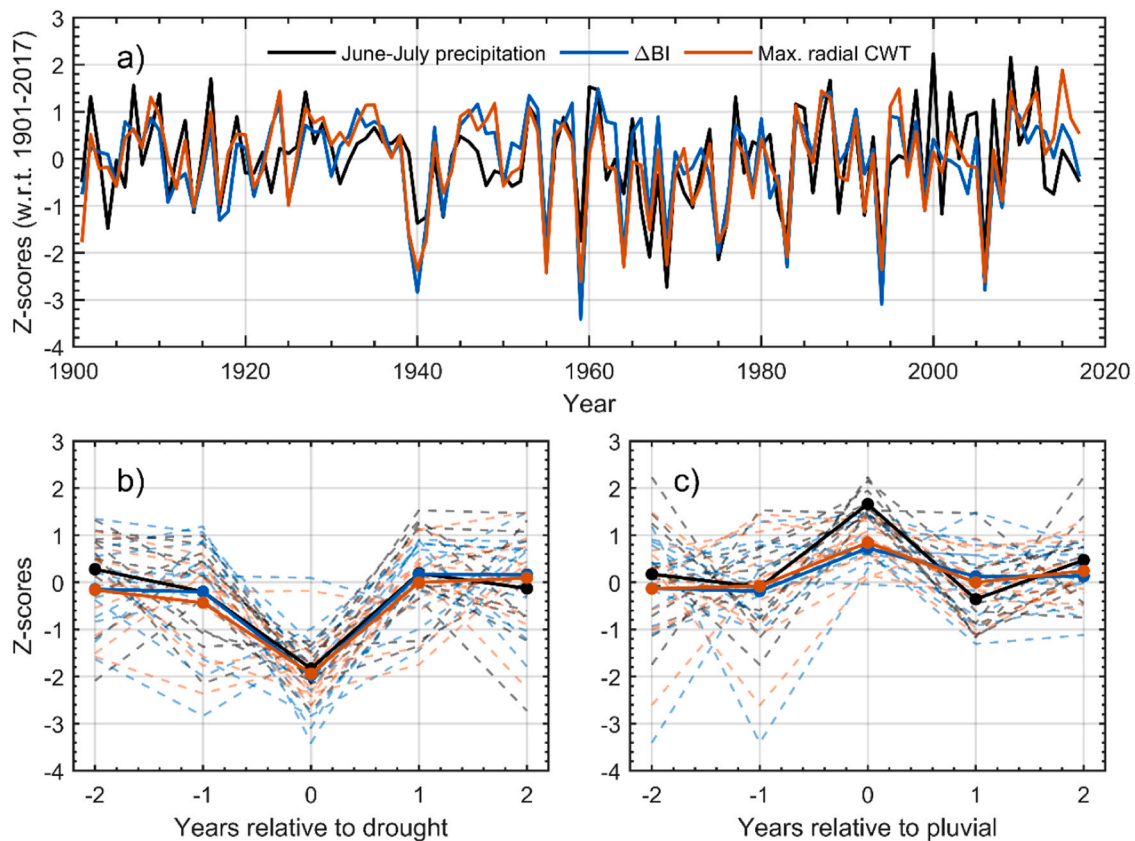


Fig. 4. a) Linearly detrended time series of June-July average precipitation, Δ BI and max. radial CWT. b) – c) Results of the superposed epoch analysis. Tree-ring response to extremely dry and wet years, based on the lower and upper 10th percentiles of average June – July precipitation, and two years before and after the extreme event. The dashed lines represent individual years, whereas the bold lines show the averages for all the considered years. Scaled precipitation indices are added for comparison (black lines).

altered carbon allocation dynamics during periods of abundant moisture, where surplus photosynthate is either allocated to compartments other than the stem or stored as non-structural carbohydrates for potential use in subsequent years (Dannenberget al., 2019). Potential data-related issues could arise from the current regional aggregation of the CRU TS 4.07 dataset, which might smooth out local-scale summer convective precipitation events while capturing larger regional droughts. This imbalance could affect the tree-ring response to precipitation by distorting the representation of wet and dry extremes. However, when using local precipitation data from the Visby Airport Meteorological Station (WMO station code 2590), located approximately 30 km from the study site, we observed the same non-linear precipitation response (results not shown). This suggests that the observed non-linearity is unlikely to be attributable to the characteristics of the CRU TS 4.07 dataset.

Turning from the extremes to the full range of warm-season precipitation, we see that non-linear (quadratic) regression outperform linear regression in terms of explained variance (R^2) for both Δ BI and maximum radial CWT (Fig. 5c-d). This finding supports the notion that non-linear precipitation-growth responses work best for the current site and species. The linear regression accounts for 44 % of the fractional variance in Δ BI and 52 % in maximum radial CWT. The non-linear models, on the other hand, enhance predictive accuracy with 6 percentage point increase in explained variance for both tree-ring parameters. While these improvements may appear trivial, relying on linear relationships in reconstruction efforts could lead to an overestimation of the drought severity or an underestimation of the extremely wet years, significantly affecting how recent European drying compares to historic drought extremes. This underscores the importance of accurately modeling the asymmetric climate-growth response in future

reconstruction efforts that utilize BI and other densitometric measurements from *Pinus sylvestris* forests in Gotland. Additional research that moves beyond the commonly used empirical statistical methods is needed to examine the threshold for the non-linearity and various endogenous and exogenous controls on the tree-ring parameters that create this curved growth response. One promising avenue is the implementation of the non-linear Vaganov-Shashkin forward model of tree-ring formation (Vaganov et al., 2011), which could help estimate the optimal threshold values associated with the dry-biased asymmetry and ultimately improve model fit and uncertainty quantifications in future hydroclimate reconstruction efforts.

4. Concluding remarks

We present what we believe to be the first systematic benchmarking of moisture-sensitive tree-ring blue intensity (BI) records against quantitative wood anatomical (QWA) measurements, emphasizing low-frequency variance and their ability to capture hydroclimate extremes. Our focus is on *Pinus sylvestris* from drought-prone marginal forests in the predominantly cold and humid region of Fennoscandia. The scarcity of moisture-sensitive proxies in this and other high-latitude areas, combined with our findings, underscores the need for further exploration of both new and traditional hydroclimate proxy parameters. This research is particularly timely given the recent increase in climate-related extreme events in northern latitudes - such as the European drought observed in 2018 - which often have more significant impacts on humans and ecosystems than average climate changes. Contextualizing these events within a long-term framework is vital for understanding potential changes in their frequency and return intervals over time.

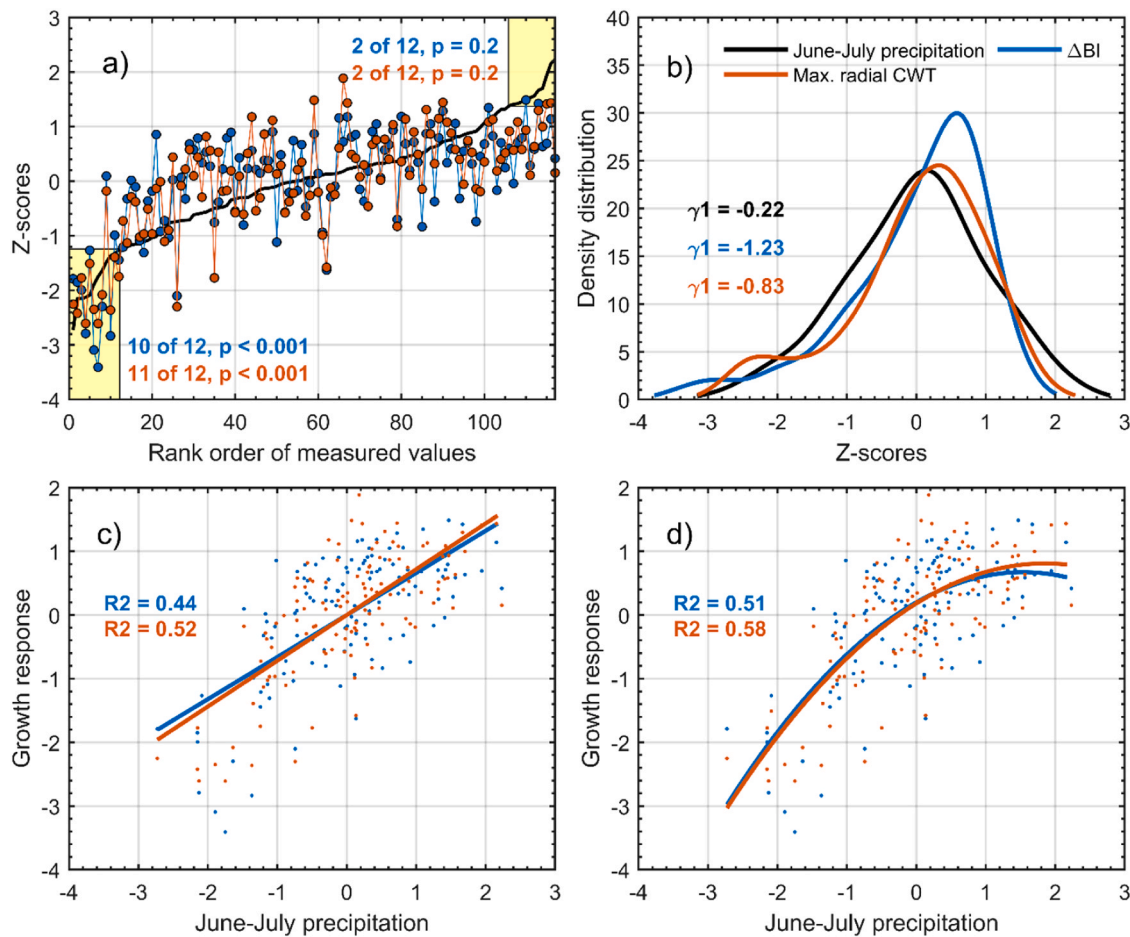


Fig. 5. a) Results of the non-parametric Extreme Value Capture (EVC) test. The Δ BI and max. radial CWT chronologies are compared against average June-July precipitation, presented in rank order. The yellow boxes encompass the lowest and highest 10th percentiles, containing 12 years each. b) The density distributions of warm-season precipitation and tree-ring data over the common 1901 – 2017 period, including the associated coefficients of skewness (γ_1). c) – d) Relationship between the tree-ring parameters and warm-season precipitation. Linear and quadratic regression fits are added, along with the variance accounted for by each model (R^2) adjusted for degrees of freedom. All panels are based on data that has first been linearly detrended and then z-scored relative to the 1901–2017 period.

Results presented here show comparable warm-season precipitation sensitivities in the BI records as in the QWA analogs at the inter-annual time scale, with distinct and largely not overlapping precipitation signals embedded in the earlywood and latewood components of the ring. Peak correlation with warm-season precipitation is strongest for the maximum radial CWT, yet only slightly weaker for LWBI. In both cases, over 50 % of warm-season precipitation variability can be explained at the inter-annual time scale, suggesting that using latewood density as a predictor has potential to significantly improve existing tree-ring hydroclimate reconstructions from the region, which have primarily relied on the conventional ring width parameter. However, at longer time scales, LWBI is clearly affected by heartwood – sapwood color differences which produce a biased long-term trend in the chronology. The Δ -adjustment of the BI parameters appears effective in neutralizing these color differences; nevertheless, further investigation is required to assess the lower frequencies when integrating archaeological or relict wood material into extended chronologies. Furthermore, the quantification of extreme capture indicates an asymmetrical behavior in the Δ BI parameter. While Δ BI effectively captures dry extremes with high fidelity, it may overestimate these extremes when compared to their corresponding QWA counterparts. In contrast, wet extremes are insufficiently represented in both BI and QWA-based proxy datasets. This pronounced curvature in the relationship between precipitation and latewood density must be carefully considered in future studies aiming to reconstruct hydroclimate from tree-ring data.

The findings presented here indicate that BI records merit serious consideration as cost-effective alternatives or complement to X-ray densitometry and QWA in future hydroclimate research in Fennoscandia. The signal strength and climate imprint of BI are comparable to these more expensive and time-consuming methods. These results are particularly promising given the wealth of historical tree-ring material available in this region, much of which has not yet been utilized for hydroclimate studies (Bråthen, 1995).

CRedit authorship contribution statement

Kristina Seftigen: Writing – original draft, Visualization, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jesper Björklund:** Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Fonti Marina:** Writing – review & editing, Formal analysis. **Georg von Arx:** Writing – review & editing, Software, Resources, Project administration, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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