Dendrochronologia 90 (2025) 126304

Contents lists available at ScienceDirect

Dendrochronologia

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

A Norway spruce Blue Intensity summer temperature reconstruction from the Central Scandinavian Mountains

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ARTICLE INFO

Keywords:
Dendroclimatology
Blue Intensity
Norway spruce
Temperature reconstruction
Jämtland
Central Scandinavian Mountains

ABSTRACT

Fennoscandia is a favourable region for dendroclimatological research. Yet, most of the dendroclimatological research in Scandinavia has focused on Scots pine (*Pinus sylvestris* L.) while fewer studies have focused on Norway spruce (*Picea abies* L.), despite its wide distribution. In the present study we explore the potential of increasing the fidelity of the climate information from Norway spruce tree-ring data by investigating Late Wood Blue Intensity (LWBI) measurements from trees sampled at the elevational tree line in the Central Scandinavian Mountains. We present -to the knowledge of the authors- the first LWBI chronology and summer temperature (June through August) reconstruction based on LWBI measurements from the species, which covers the period 1750–2020. The LWBI chronology has a substantially stronger temperature signal than its corresponding tree-ring width (TRW) chronology, and displays a good spatial representation across the Nordic countries. The temperature reconstruction follows the general patterns of the temperature history previously reported for the central Scandinavian mountains. This suggests that Norway spruce and the LWBI technique are viable for studying past climate history and evaluating ongoing changes. The introduction of another species in dendroclimatic reconstructions in the area could yield more precise insights of regional climate variations, as different species exhibit varying sensitivities to climatic conditions. However, while Norway spruce can be preserved for a long time under favourable conditions, the use of Norway spruce subfossil wood in LWBI research is untested. Therefore, further research is required to develop longer Norway spruce LWBI chronologies and to fully evaluate the potential of using Norway spruce in dendroclimatic studies.

1. Introduction

In the context of climate change, the examination of past climates is essential to understand natural climatic variability. In recent decades there has been an increase of climate proxies extending over centuries to millennia which have greatly enhanced our understanding of past natural climate variability (e.g. PAGES2k Consortium, 2017). These efforts have improved our general understanding of the climate system and climatic fluctuations over time and space.

Tree rings are one of the most utilized climate proxies because they provide information/data with annual resolution which can be calibrated against observational records (Jones et al., 2009). This paleoclimate archive is widely used in regional to global climate reconstructions, and the number of tree-ring chronologies is continuously increasing, albeit with large differences regarding their spatiotemporal distribution (e.g., St. George, 2014). Because of large areas of relatively untouched forests and favourable conditions for wood preservation in bogs and lakes, Fennoscandia is a favourable region for dendroclimatological research (Linderholm et al., 2010). Most of the dendroclimatological research in Scandinavia has focused on Scots pine (*Pinus sylvestris* L.) due to both its reliable climate signal and long lifespan of trees. Fewer studies have focused on Norway spruce (*Picea abies* L.), despite its wide distribution. Norway spruce is an opportunistic species and relatively adaptable to biotic variations (Mäkinen et al., 2003; van der Maaten-Theunissen et al., 2013). The climatic sensitivity of spruce shows clear regional differences in Fennoscandia, where moisture availability is mainly a limiting factor for radial growth at lower elevation and latitude, while temperature becomes a more important factor at higher elevation and latitude (Mäkinen et al., 2002; Andreassen et al., 2006; Seftigen et al., 2015). From a dendroclimatological perspective, the lesser interest in Norway spruce compared to Scots pine may be related to difficulties obtaining multi-century length records due both to its comparatively shorter life span (400 years vs. 700 years, respectively; Castagneri et al., 2013; Linderholm et al., 2014) and

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https://doi.org/10.1016/j.dendro.2025.126304
Received 20 June 2024; Received in revised form 28 January 2025; Accepted 8 February 2025
Available online 11 February 2025
1125-7865/

its decay-prone nature, thereby making the presence of remnant material with an exterior ring dating prior to the 20th century extremely rare (Storaunet and Rolstad, 2002). However, Rocha et al. (2021) presented the first Norway spruce temperature reconstruction spanning two millennia, also demonstrating that wood from Norway spruce can be preserved for a long time under favourable conditions.

Tree-ring width (TRW) is the most widely used proxy for climate reconstructions since it is the easiest tree-ring parameter to obtain. Depending on the growth environment, TRW can provide useful information about growing season conditions (Fritts, 1976). However, at high latitudes in the Northern Hemisphere, maximum latewood density (MXD; Schweingruber et al., 1978) generally shows stronger agreement with instrumental temperature observations than TRW does (e.g. Franke et al., 2013; Lücke et al., 2019). Because of its comparatively stronger temperature signal, MXD may be preferred for accuracy, but at a higher work effort and cost. Aiming to find an affordable and less laborious alternative to MXD with similar quality, McCarroll et al. (2002) showed that blue light intensity reflectance/absorption (BI) from digital images of tree rings could be used as a surrogate for MXD. Since then, BI has been further explored (see e.g. Campbell et al., 2007; Rydval et al., 2014; Björklund et al., 2014, 2015) and is now established in the scientific community (Kaczka and Wilson, 2021). The method is still developing, e.g., regarding its utility for different species. For example, non-climatic colour variations in the wood, such as the lighter sapwood and darker heartwood in some conifers, can bias BI-measurements (Björklund et al., 2014, 2015; Wilson et al., 2019). Norway spruce generally do not have distinct colour variations, making it a good candidate species for this methodology. Although BI has been tested on *Picea abies* in central Europe (Kaczka et al., 2018) and different *Picea* species in North America (*P. rubens* Sarg., Heeter et al. 2019 and *P. glauca*, Wilson et al. 2019), no reconstructions have yet been attempted in Fennoscandia.

In the present study we build on the results from Rocha et al. (2021) by exploring the potential of increasing the fidelity of the climate information from Norway spruce tree-ring data by investigating Blue Intensity (BI) measurements from trees sampled at the altitudinal tree line in the Central Scandinavian Mountains. Our aim is to present the first summer temperature reconstruction based on BI measurements from the species. We hypothesize that Norway spruce is a good candidate for BI studies and that it will be a stronger proxy for summer temperature than TRW, similar to that of BI measurements from Scots pine.

2. Materials and methods

2.1. Study area

The study area is located east of the main divide of the Scandinavian mountains (Fig. 1) and belongs to the Northern Boreal zone. The topography is generally characterized by glacially eroded gentle slopes with elevations ranging from 600 to 1100 m a.s.l., occasionally rising to elevations around 1700 m.

Local climate is influenced by the proximity of the Norwegian Sea due to the convection of maritime air masses as a combined effect of the dominant westerly wind flow and the general low elevation of the mountains together with major east-west oriented valleys. Regional climate is also strongly influenced by the North Atlantic Oscillation (NAO) (Chen and Hellström, 1999; Folland et al., 2009). Mean annual temperature at the closest meteorological station with a long record (*Storlien)* is 2.1 °C with the coldest month being February (-5.8 °C) and the warmest month July (12.2°C). Average monthly precipitation is 74 mm, with the wettest month being August (99 mm) and the driest month being April (45 mm) (1991–2020; *Storlien*, data from the Swedish Meteorological and Hydrological Institute, SMHI, 2022).

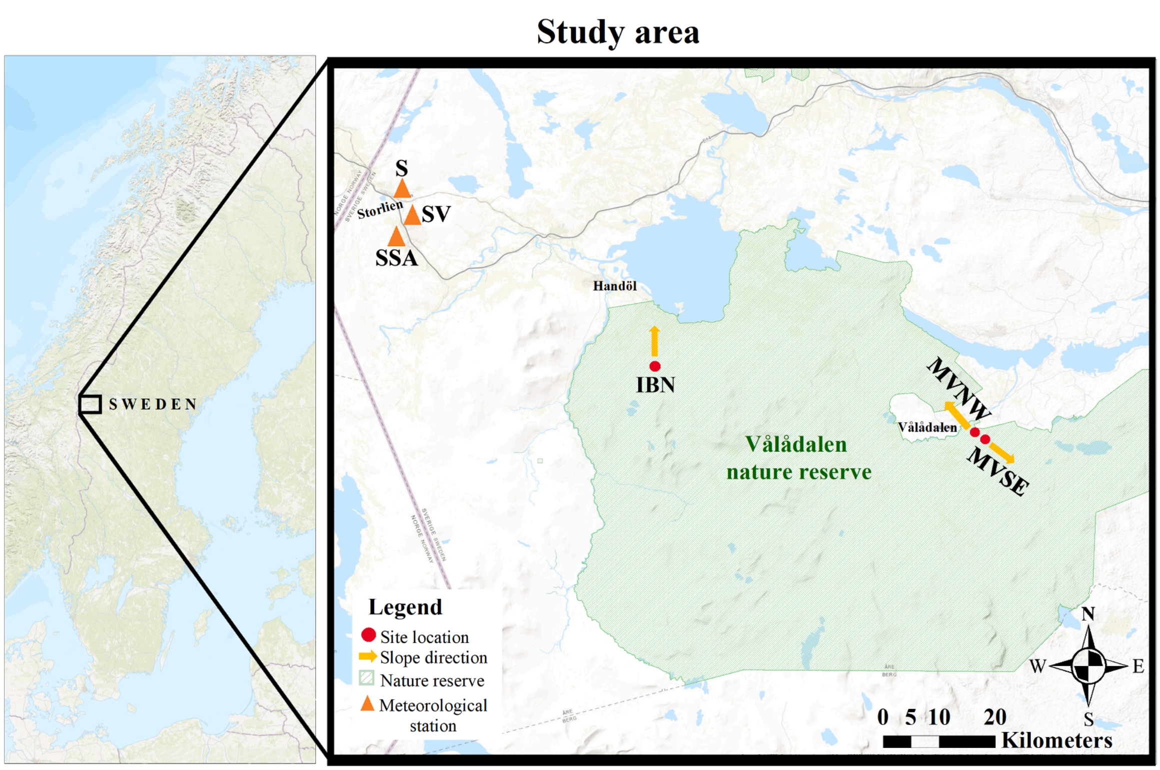

Fig. 1. Location of the study area in Sweden (left) and a detailed map section from Vålådalen nature reserve (right). The red dots indicate the location of the sampling sites with slope direction displayed by the yellow arrow. IBN=North-facing slope on Ierhkiebielie. MVNW and MVSE= Northwest and southeast facing slopes of Middasvalen respectively. The orange cones indicate the three locations of the meteorological station near Storlien. S=Storlien station, SV=Storlien-Visjövalen and SSA=Storlien-Storvallen A.

2.2. Study sites

Spruce samples for dendroclimatological analysis were collected at three tree-line sites within the Vålådalen nature reserve (Fig. 1). No logging or other human disturbances were evident. The vegetation at the sampling sites were dominated by grasses and shrubs, with the field layer being commonly composed of *Ericacea* species such as crowberries (*Empetrum nigrum*); lingonberries and blueberries (*Vaccinium vitis-idaea*, *Vaccinium myrtillus resp.*) and dwarf birch (*Betula nana*). The tree species included Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris* L.), mountain birch (*Betula pubescens*) and Juniper (*Juniperus communis*). The upper treeline (in this study defined as the elevational limit of any individual >2 m in height), is populated by mountain birch, followed by Norway spruce and Scots pine at lower elevations. The soils are thin and consist of till, lacustrine sediments and glaciofluvial deposits (Lundqvist, 1969). The vegetation at the tree line is often interspersed by bedrock.

Two sites lying ca. 27 km apart from each other were chosen for the sampling, Mount Middagsvalen (Fig. 2a) and the northern slope of Ierhkiebielie (Fig. 2d). The spruce tree-line is characterized by 'tree islands' with multiple spruce individuals growing together or solitary trees.

At Middagsvalen (880 m a.s.l.) samples from two slopes were collected, north-west and south-east. The steepness of the NW slope varies between 20 and 30° near the treeline, and 5 to 15° downslope towards the forest-line (Fig. 2b, MVNW, 63°8′41 N, 13°2′42 E). This site was rather mesic, with variable moisture availability at the microsite level. The spruce treeline was found at 819 m a.s.l. (+/−3 m), ca. 35 m above the forest line (limit), but newly established saplings were found above the treeline. The slope facing SE is steeper, varying from 30 to 45° and from 15 to 30° downslope near the continuous forest (Fig. 2c, MVSE, 63°8′27 N, 13°2′54 E). Compared to the NW slope, the SE was drier, and trees were found growing in depressions where the soil moisture likely was higher. Here the spruce treeline was found at 844 m a.s.l (+/−3 m), ca. 45 m above the forest line.

The north-facing slope of Ierhkiebielie was sampled (Fig. 2d, IBN, 63°12'28 N, 12°32'16 E). The slope steepness varies between 0 and 10° from the treeline to the continuous forest and the site is evidently more moist when compared to the previous sites. Trees were growing in bigger groups up to the treeline and no saplings or smaller spruces were growing above the treeline. The spruce treeline was found at 745 m a.s.l. (+/−3 m), ca. 15 m in elevation above the continuous forest. The site had the highest average tree age (Table 1) and there were only a few young trees found in total.

2.3. Sample collection and preparation

Norway spruce were sampled with a 5.17 mm-diameter increment borer at an average of 70 cm above the ground (lower than 'breast height' to sample more rings), avoiding irregularities such as branches, knots and reaction wood, and prepared according to standard dendrochronological techniques (Stokes and Smiley, 1996). The largest trees (expected to be the oldest) were selected for sampling to attain a longer

Table 1
Tree-ring statistics from samples collected at each site.

Site	NS	NSBI	TA(M-A-M)	TS	RBAR	MS
IBN	47	35	22–131–347	1675–2021	0.419	0.069
MVNW	47	36	25–107–372	1650–2021	0.450	0.073
MVSE	43	33	20–59–162	1860–2021	0.369	0.063
Total:	137	104				

NS, Number of trees sampled; NSBI, Number of samples used for BI; TA(M-A-M), Tree age (min-average-max); TS, Time span of chronology; RBAR, interseries correlation (BI); MS, Mean sensitivity (BI).

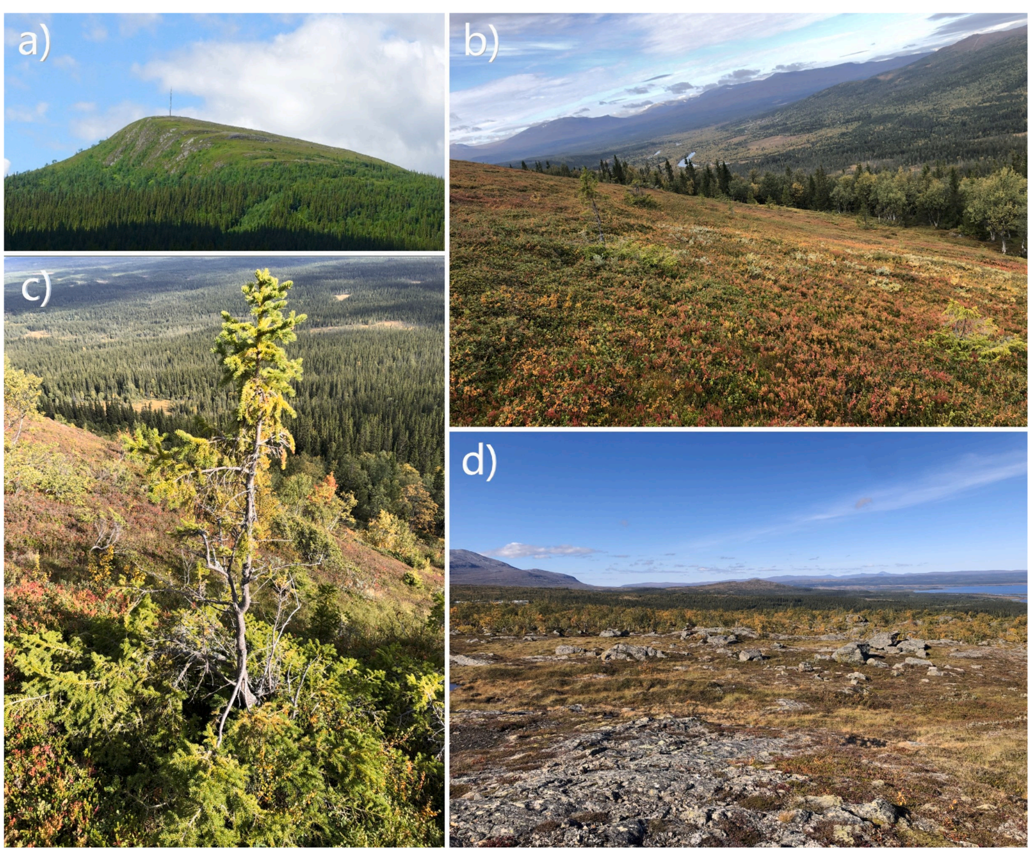

Fig. 2. The study locations; showing mountain Middagsvalen: (a), the north-western slope of Middagsvalen MVNW: (b), the south-eastern slope of Middagsvalen MVSE: (c) and the northern slope of Ierhkiebielie IBN: (d).

time span in the chronology. A total of 137 trees were sampled across all three sites, with a tree age spanning between 20 – 372 years (Table 1).

To facilitate chronology building, all samples were visually cross-dated, and later annual tree ring increments were measured on a Lintab sliding measuring system connected to the Time Series Analysis Program (TSAP-Win 4.70b) software (Rinntech, Heidelberg, Germany) with a precision of 0.001 mm (1 μm) under a microscopic magnification of 10x/25. Two radii from each tree were used. For each pair of measurements (i.e., within-tree samples) student's *t*-test values and the cross-date index (CDI) calculated by TSAP was used to ensure the radii were in agreement. If well correlated, the two radii were averaged to one series for the individual tree. Subsequently, all tree-ring series were cross-dated against each other. The cross-dating accuracy was assessed using the program COFECHA (Holmes, 1983). In periods of low replication, the Norway spruce tree-ring width chronology from the same area by Rocha et al. (2021) was used to facilitate cross-dating.

Following visual and statistical control, samples were selected for BI measurements. A number (15) of younger trees (<40 years) were left out to get a more even spread of age groups at each site. Also, tree-ring series with signals that significantly deviated from those of other trees (15) and samples with large colour variations (3) were also excluded. A total of 104 samples were selected for BI measurements. Since most of the remaining spruce samples had relatively even colour and almost no resin throughout the cores, no ethanol wash was performed (Wilson et al., 2019; Heeter et al., 2019). The samples were scanned to 3200 dots per inch (DPI) by means of an Epson (Perfection V600) scanner calibrated with an IT8.7/2 colour card using the SilverFast (LaserSoft Imaging) scanning software. The scanned images were subsequently measured and cross-dated against the previous TRW-version of the exact same individuals using the CooRecorder/CDendro (version 8.1, www.cybis.com) software. Subsequently, a test was conducted to compare the temperature signal of 20 Norway spruce BI-series generated in CooRecorder using mean latewood blue intensity (LWBI), mean earlywood blue intensity (EWBI) and DeltaBI (latewood-earlywood, Björklund et al., 2014). LWBI had the highest temperature correlations with instrumental data and better intercorrelation between samples. Thereby, LWBI data were chosen for the full chronology. LWBI data was generated using 50 % of the darkest pixels of the latewood portion of each annual ring. A colour intensity calibration curve was created and implemented before the final LWBI extractions (Cybis, 2016). The LWBI from different radii belonging to the same tree was averaged, as for TRW.

2.4. Standardization

Tree ring width usually exhibits a decreasing growth trend as a tree gets older, which is unrelated to environmental conditions. This biological age trend needs to be removed to enhance the information associated with climate in the tree ring data (Fritts, 1976). In this study we used an age dependant spline (ADS) with the software ARSTAN (Cook and Krusic, 2005) to remove the age trend. The standard chronology (STD) was used in our analyses. The ADS conforms to the idea that radial growth decreases with tree age, while the tree also becomes less sensitive to disturbances (Cook and Peters, 1981). The spline stiffness parameter increases as the tree gets older and tracks the growth trajectory in the tree-ring series. Furthermore, the ADS adapts to the length of the tree-ring series. Because we targeted spruce from the treeline, the proportion of age distribution is skewed to younger individuals (about 50 % recruitment from 1950), though the LWBI chronology was expected to retain a fair amount of low frequency variance considering the age of the older individuals (Cook et al., 1995). By that, using an ADS was deemed appropriate. To determine the strength of the common signal of the samples, the Expressed Population Signal (EPS) and R-bar statistics were calculated (Wigley et al., 1984). LWBI-data and TRW-data were standardized using the same approach. Since the standardized chronologies separated by sampling site were highly similar (Fig. 3), the samples from the three sites were averaged into one LWBI and one TRW chronology, and called Vålådalen (with MVNW and IBN being more similar ($r = 0.87 < 0.01$) while MVSE was slightly different from the others ($r = 0.66$ and $r = 0.62 < 0.01$ for MVNW and IBN respectively) which likely stems from a dominance of younger trees at MVSE).

2.5. Statistical analysis and temperature reconstruction

Climate data were retrieved from the closest meteorological stations in Storlien (SMHI, 2022). Continuous meteorological data exist from 1899, although the station has been moved about 5 km on two occasions. To determine the climate signal in the tree-ring data, the LWBI - and TRW-chronologies were correlated against monthly mean temperature and total precipitation data. The DendroClim2002 software (Biondi and Waikul, 2004) was used to calculate significant Pearson correlations ($p < 0.05$). Temperature averages of multiple summer months were used to identify the optimal target season. Spatial correlation maps of the LWBI and TRW chronologies and 0.5° gridded CRU TS 4.05 climate data were downloaded using the climate explorer tool provided by the Royal Netherlands Meteorological Institute (https://climexp.knmi.nl/start.cgi) (Trouet and Oldenborgh, 2013). Subsequently, a temperature reconstruction model was created using linear regression with the software PAST (Hammer et al., 2001). A split sample validation analysis was conducted to determine the temporal stability of the model, where the full data period (1900–2020) was split into two sub-periods: 1900–1959, 1960–2020 (Snee, 1977). To validate the quality of the model, the mean square error (MSE), square root of MSE (RMSE), coefficient of efficiency (CE) and reduction of error (RE) statistics were calculated (National Research Council, 2006).

3. Results

The Vålådalen LWBI and TRW chronologies (z-scored) are presented

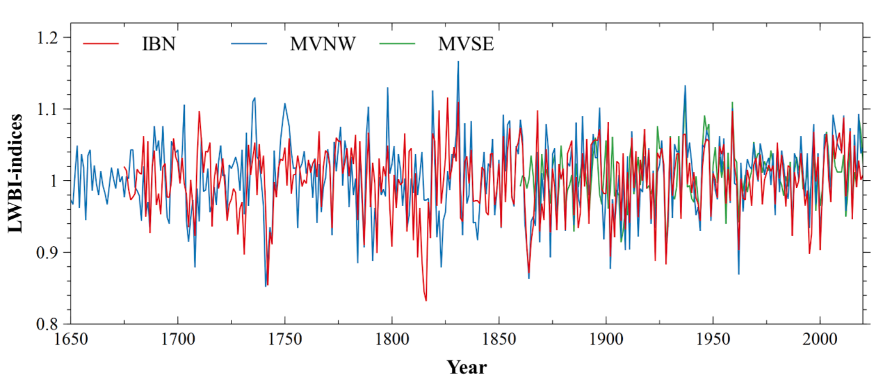

Fig. 3. Latewood Blue Intensity indices 1650–2020 separated by sampling site, showing the chronologies IBN (red), MVNW (blue) and MVSE (green).

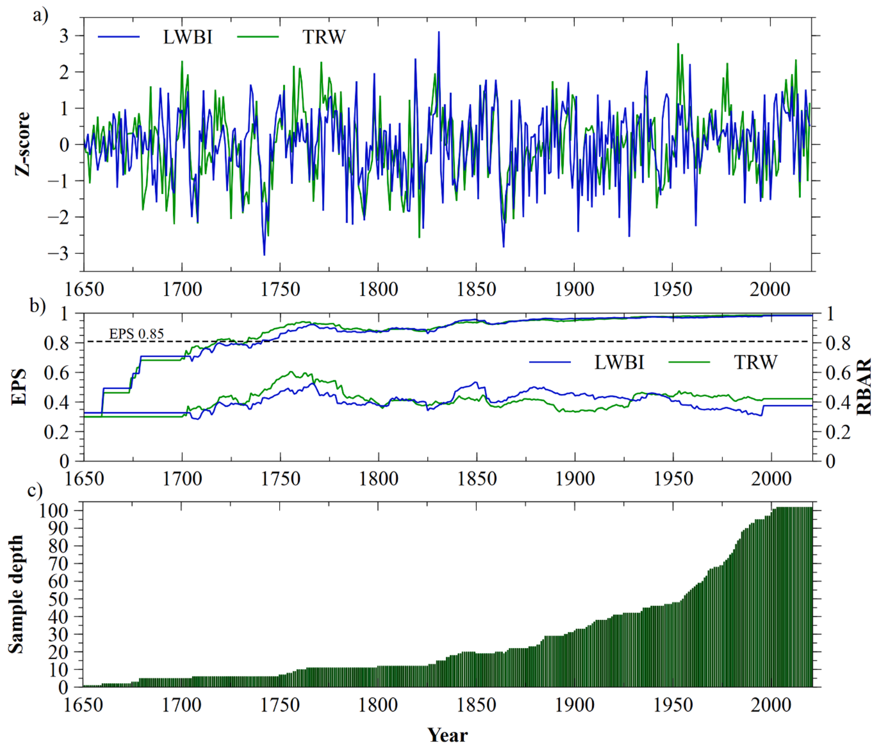

Fig. 4. a) The Vålådalen chronologies 1650–2020 (LWBI in blue and TRW in green) with the temporal evolution of the chronologies (z-scored, calculated over the common period 1650–2020); b) the EPS (upper series) and RBAR (lower series) of the chronologies and c) the sample depth of the chronologies.

in Fig. 4a. The chronologies consist of 104 samples and span 1650–2020 (371 years) with a mean segment length of 103.5 years. The sample depth is low in the earlier parts of the chronologies, with only one series extending to 1650, 5 series to 1679 and 10 series to 1759 (Fig. 4c). The LWBI chronology has a series intercorrelation of $r = 0.565$ and a mean sensitivity index of 0.070. The EPS of the LWBI chronology surpasses the 0.85 threshold from 1750 and the average RBAR (1650–2020) is 0.4 (Fig. 4b). The TRW chronology has a series intercorrelation of $r = 0.642$ and a mean sensitivity index of 0.285. The EPS of the TRW chronology surpasses 0.85 from 1742 and the average RBAR (1650–2020) is 0.41. The TRW data have a higher first-order autocorrelation (1-year lag) than the LWBI data ($r = 0.40$ (TRW) and $r = 0.08$ (LWBI)).

3.1. Comparing the climate signal between LWBI and TRW

The temperature signal in the Vålådalen LWBI chronology is more pronounced than in the TRW chronology. The LWBI chronology correlates significantly (1900–2020, $p < 0.05$) with monthly temperatures from April to September ($r = 0.19 – 0.67$), with the highest correlation reached for temperature data in July ($r = 0.67$) and the seasonal average from June through August (JJA) ($r = 0.79$) (Fig. 5a). The TRW chronology correlates significantly (1900–2020, $p < 0.05$) with monthly temperature data from May to July ($r = 0.20 – 0.46$), reaching the highest correlation with temperature data in June ($r = 0.46$) and the seasonal average from June through August (JJA) ($r = 0.41$). Apparently, both chronologies are significantly (1900–2020, $p < 0.05$) and negatively correlated with precipitation during summer, correlating most strongly with average precipitation from June through August (JJA) (LWBI $r = -0.4$; TRW $r = -0.28$) (Fig. 5b). The LWBI chronology shows significant negative correlations with monthly precipitation from June to August ($r = -0.24$, $p < 0.05$), while the TRW chronology only shows significant negative correlation with June precipitation ($r = -0.23$, $p < 0.05$). However, the relationship with precipitation is not entirely clear, since partial correlations controlling the effects of temperature indicate barely or non significant correlations ($p = 0.09$ and $p = 0.049$ for precipitation totals in JJA and MJJA respectively). The spatial temperature correlation patterns between gridded JJA temperature data (CRU TS4.05; Harris et al., 2020) and the LWBI (Fig. 5c) and TRW (Fig. 5d) chronologies reveal a stronger temperature signal in the LWBI data. The LWBI chronology correlates well ($r > 0.6$, $p < 0.05$) with temperatures across most of the Nordic and Baltic countries, while the temperature signal in the TRW chronology is weaker ($r = 0.4–0.5$, $p < 0.05$) and more centred around the study area, with lower correlations ($r = 0.3–0.4$, $p < 0.05$) across most of the Nordic and Baltic countries.

3.2. Temperature reconstruction

Given the stronger temperature signal in LWBI compared to TRW, only the former was used here to develop a summer (JJA) temperature reconstruction. The calibration and verification statistics indicated a stable relationship between the LWBI data and observed temperatures, with a slightly stronger relationship in the early period (1900–1959: R^2=0.66, CE=0.61) compared to the late period (1960–2020, R^2=0.61, CE=0.54). Both RE and CE are positive, indicating the skill of the model for predicting temperature variability. For the full 1900–2020 calibration period the R^2-value is 0.63 and the MSE/RMSE of 0.6/0.77 provide an estimate of the degree of agreement between predicted and observed values (Table 2).

There is a strong linear relationship between the LWBI chronology and observed JJA temperatures (Fig. 6a), and a good agreement on interannual timescales ($r = 0.80$ $p < 0.01$) is apparent (Fig. 6b). On longer timescales, three features stand out: a more stable warming trend in the last 160 years, lower variance from the early 1960s and onwards compared to the first ca 200 years, and more variability of cold and warm periods in the first half of the reconstruction compared to the second half. Colder decades are found in the 1790 s, the 1810s, the 1860s and the early 1900s. Warmer decades in the 1770 s, the 1830s, the 1850s, the 1880s, 1930s, 1970s and the 21st century.

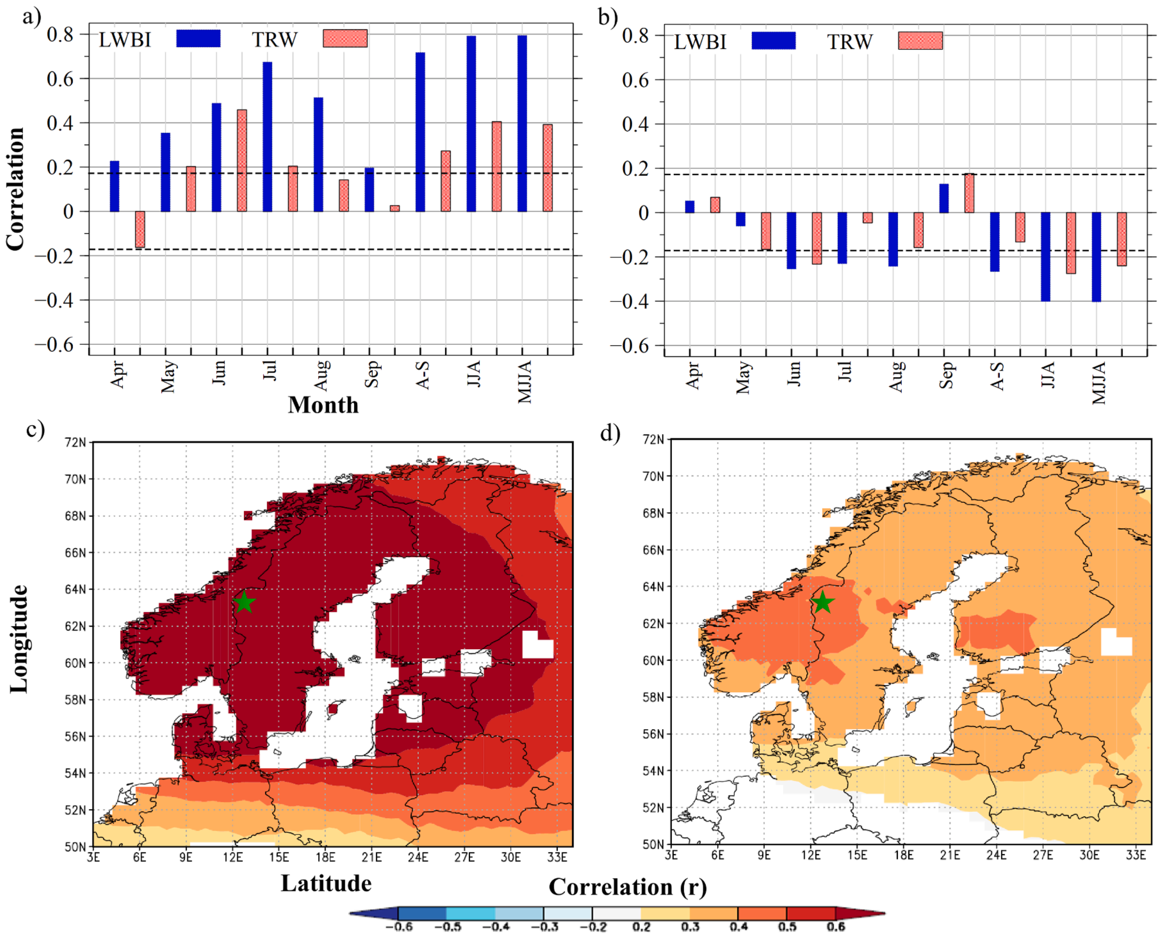

Fig. 5. The climate signal of the Vålådalen LWBI and TRW data, for (a) temperature and (b) precipitation, showing the correlations with instrumental observations from the meteorological stations near Storlien (SMHI, 2022). Along the X axis, individual monthly averages and seasonal averages for the months of April through September (A-S), June through August (JJA) and May through August (MJJA). All correlations calculated for present-year data over the 1900–2020 period. The dotted line shows the significance boundary (95th percentile range). The lower panels show the spatial correlation between June-August average temperature from the CRU TS4.05 dataset (Harris et al. 2020) with the LWBI chronology (c) and the TRW chronology (d) (computed using the KNMI Climate explorer, Royal Netherlands Meteorological Institute (https://climexp.knmi.nl/start.cgi). Calculated over the 1901–2020 period. The green star shows the study location.

Table 2
Calibration and verification statistics of the Vålådalen JJA temperature reconstruction.

Calibration period:	1900–1959	1960–2020	1900–2020
Explained variance R^2	0.66	0.61	0.63
Number of observations	60	61	121
Verification period:	1960–2020	1900–1959	
RE	0.6	0.65	0.63
CE	0.54	0.61	
MSE/RMSE	0.62/0.79	0.7/0.84	0.6/0.77

4. Discussion

This study presents the first LWBI based reconstruction from Norway spruce in Scandinavia. Several BI-reconstructions based on Scots pine have been published (e.g., Trachsel et al., 2012; McCarroll et al., 2013; Björklund et al., 2015; Fuentes et al., 2018), similarly, multiple blue intensity chronologies were presented on Engelmann spruce from north America (Heeter et al., 2020, 2021). In this study we focus on *Picea abies* with the intent of diversifying the use of available species for temperature reconstructions in this region. As such, our results suggest that *P. abies* is an amenable alternative to *Pinus sylvestris*, which is by far the most used species to reconstruct climate in Scandinavia either using BI, TRW or MXD (e.g., Linderholm and Gunnarson, 2005; Gunnarson, 2008, Esper et al., 2014, Björklund et al., 2015; Linderholm and Gunnarson, 2019; Seftigen et al., 2020). Considering that studies are mainly developed on the same species with wide geographic distribution, there is a possibility of a bias in the final reconstructions due to the species-specific responses to the environmental settings, i.e., traits depending on phenology and the genetic pool of the populations (see Salmela et al., 2013). The use of multiple species for dendroclimatic reconstructions is generally positive as it provides more details of regional climatic variation depending on differences in the species sensitivities to certain environmental variables, such as temperature, precipitation, target season, elevation etc. (e.g., Frank and Esper, 2005; Maxwell et al., 2015; Alexander et al., 2019). Analysis of the *Picea abies* temperature signal indicates dependency on the period between early to middle (May-August) summer temperature. This could complement the temperature signal of *Pinus sylvestris* which tends to capture middle to late (July-September) summer temperature and have a weaker response towards temperatures in May and June (e.g., Linderholm and Gunnarson, 2005; Zhang et al., 2016; Fuentes et al., 2018; Semenyak and Dolgova, 2023). The observed variations in temperature signal might be due to physiological differences between the species that may be observed in phenological differences (Stridbeck et al., 2022). Norway spruce is regarded as a shade-tolerant species (Caudullo et al., 2016) and Scots pine as a light-demanding species (Durrant et al., 2016). Theoretically, the shade-tolerance of spruce could enable the species to photosynthesize on days and periods when pine photosynthesis is

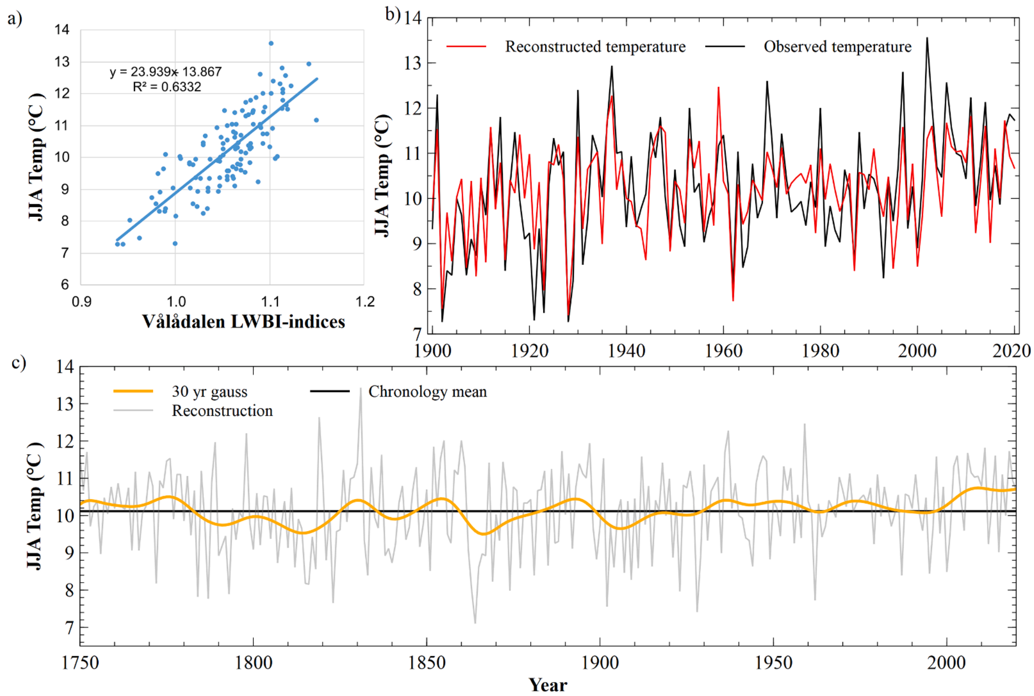

Fig. 6. plate a) Scatter plot of observed JJA mean temperature and the Vålådalen LWBI chronology. b) Comparison of reconstructed (red) and observed (black) JJA mean temperature 1900–2020. c) The Vålådalen LWBI reconstruction of JJA mean temperature 1750–2020 (EPS >0.85) is plotted in grey. The yellow plot shows the 30-year Gaussian low-pass filtered version of the reconstruction. The straight black line is the chronology mean (10.1°C).

marginal (e.g., cloudy days).

The effects of moisture conditions as a cause of differing temperature signals may be difficult to assess with the data obtained in this study: Scots pine is considered drought-tolerant (Durrant et al., 2016) while Norway spruce is rather sensitive to summer drought (Caudullo et al., 2016). Given that the tree-line environments we visited are rather drought prone during the summer months due to the high angle of the slopes, shallow soils, soil properties and strong winds, a significant negative correlation with precipitation during the growing season is not altogether consequent since it may be interpreted as an effect of adverse conditions or alternatively, of enhanced cloudiness. While an association between cloudiness/sun light and tree growth has been found in relation to Scots Pine in Scandinavia (e.g. Gagen et al., 2011; Seftigen et al., 2011) it has not been explored for Norway spruce, perhaps since it is a shade tolerant species it has received less attention as a source of dendrochronological data. Moreover, the -*a priori*- negative correlation with precipitation becomes non-significant when partial correlation tests are run controlling the effects of temperature as correlation values drop to marginally significant or non-significant, indicating uncertainty.

What we know is that pine trees are better suited for hydrological conditions that may be encountered in tree-line environments, while light conditions together with the phenological differences may play a role on the observed diverging temperature signal. Thus, combining datasets of spruce and pine from the same region may reduce potential biases introduced by different climate sensitivities of the species, provide more details of climatic variation in the full summer period and perhaps offer better understanding of past climates and within-year variations. The source of the differences in climate signal should be studied further.

4.1. LWBI vs TRW

The accessibility due to the price and technical requirements makes the BI methodology attractive, since it still allows the assessments of high-quality climate signals, especially in the higher frequencies (McCarroll et al., 2002; Campbell et al., 2007; Rydval et al., 2014; Wilson et al., 2014; Björklund et al., 2014, 2015). Our results show that the temperature signal derived from LWBI tree ring indices is much more pronounced than for TRW (Fig. 5). The values reached from correlation functions between LWBI and instrumental climate data are almost $r = 0.8$ for seasonal averages of the summer months, as compared to almost $r = 0.4$ for TRW. This implies that explained variances from linear regressions between LWBI and TRW data against temperature data presented here differed by up to $r^2 = 0.38$, indicating that LWBI offers greater possibilities to achieve accurate reconstructions at the higher frequency variability. Thus, our results are consistent with previous reports on application of the BI methodology in the study area. Further, it could be expected that the interannual temperature signal is of similar strength to that of MXD (Björklund et al., 2014, 2015), although it is not tested in this study.

4.2. Comparison with other BI chronologies

To set the Vålådalen spruce LWBI chronology in a local context, we compared our results with the other two previous ΔBI chronologies developed in the area: Jämtland (Björklund et al., 2015) and Rogen (Fuentes et al., 2018). These records were developed from samples of Scots pine, thus allowing us to assess similarities and differences between these different species at nearly the same location. We find the Vålådalen chronology to have reasonably good agreement with two Scots pine ΔBI chronologies at decadal timescales (Fig. 7b-c). All chronologies indicate an increasing trend from around the 1850s and onwards, after which lower indices become less persistent and rarer. The Vålådalen LWBI-indices exhibit a short decrease after 1970, rising sharply after 1990, coinciding better with the records from Jämtland than those from Rogen (Fig. 7b-c). The Vålådalen LWBI chronology has a slightly stronger correlation with the Jämtland chronology ($r = 0.73$, $n = 258$, $p < 0.01$) compared to the Rogen chronology ($r = 0.68$, $n = 258$, $p < 0.01$), which is likely due to the close geographic proximity of the Vålådalen- and Jämtland-chronologies (Fig. 7a). The most notable variations in the Vålådalen LWBI chronology are the somewhat consistently higher indices ca. 1840–1860 and 1870–1900, as well as the

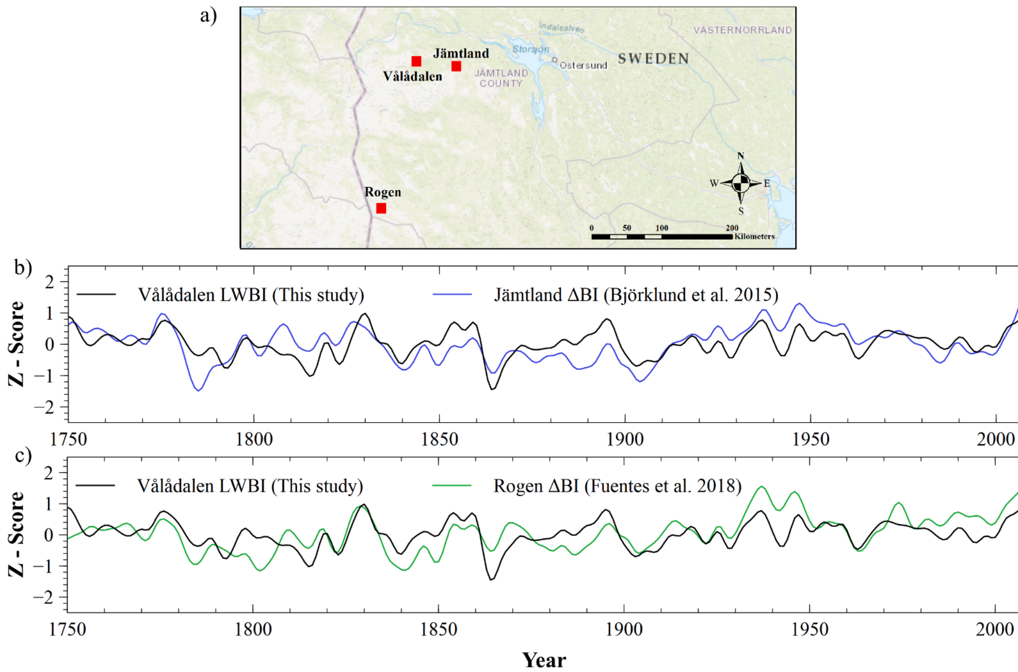

Fig. 7. Comparison of the Vålådalen Norway spruce LWBI chronology with two Scots pine-based ΔBI chronologies from nearby regions 1750–2007 (a). One Scots pine ΔBI chronology from Jämtland (b) (Björklund et al. 2015) and one Scots pine ΔBI chronology from Rogen (c) (Fuentes et al. 2018). To facilitate comparisons, all chronologies were detrended with an ADS as used in this study. Z-scores were calculated over the common period 1750–2007. The chronologies were smoothed with a 10-year low-pass Gaussian filter.

lower indices ca. 1920–1950. As a result, the Vålådalen LWBI chronology has a less pronounced increasing trend as compared to the other two ΔBI chronologies. This is likely related to the higher proportion of younger trees in the Vålådalen LWBI chronology. Younger trees are more sensitive to climatic variations and disturbances compared to older trees (Fritts, 1976) and trends of younger and older trees are likely to differ. When using a flexible detrending approach such as the ADS, a high proportion of younger trees may further cause increased lows and reduced highs in the final chronology. Thus, it is expected to be some variation in the Vålådalen series. Arguably, it may be more appropriate to examine the Vålådalen LWBI chronology with a focus on high frequency variations with less regard to longer trends. When visually comparing the chronologies on interannual to decadal variability there is good agreement between the records, albeit with differences in amplitude of the fluctuations. The similarities between the records can be interpreted as the climate sensitivity of the species and the clear dominance of temperature as a growth limiting factor. In turn, the differences between the records may be attributed to influences of microsite conditions and different habitat requirements between Norway spruce and Scots pine, which requires further studies to fully understand the mechanisms involved. Our results imply that the LWBI temperature signal is of similar strength in Norway spruce to that of Scots pine in the central Scandinavian mountains, albeit with different temperature sensitivities in the summer period. This makes it a good candidate species for LWBI research. LWBI chronologies using Norway spruce may also be created without an ethanol wash, which may save time and effort compared to using resin-rich species such as Scots pine. On the other hand, this process implies a tradeoff since it forces the removal of coloured samples diminishing the sample depth. Rocha et al. (2021) demonstrated that wood from Norway spruce can be preserved for long periods of time under favourable conditions but the use of Norway spruce subfossil wood in LWBI research is untested. Another possibility could be to use Norway spruce samples from old buildings and structures as the species has long been used for construction. Still, more research is needed if longer LWBI chronologies of Norway spruce are to be created, but there are possibilities in utilizing the species in more climate research.

5. Conclusions

Our results show that Norway spruce LWBI is a powerful temperature proxy, with greater temperature signal than TRW, and the Vålådalen LWBI June through August temperature reconstruction follows the general patterns and timing of the temperature history previously reported for the central Scandinavian mountains. This indicates the feasibility of Norway spruce and LWBI techniques to be used for studying the past climate history and assess ongoing changes. The LWBI chronology accurately portrays warmer and colder decades from the last 270 years, with good similarity in the higher frequencies when compared to ΔBI chronologies from a nearby area. The development of dendroclimatic reconstructions based on Norway spruce in an area where Scots pine is mainly used traditionally, highlights potential biases introduced by different climate sensitivities of each of the species. We encourage further investigation to address methodological issues regarding the use of Norway spruce alone and in combination with other species in Scandinavia.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Karlsson Fredrik: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fuentes Mauricio:** Writing – review & editing, Supervision, Resources, Methodology, Investigation. **Linderholm Hans W.:** Writing – review & editing, Supervision, Resources.

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.

Acknowledgements

First, we would like to than the County Administrative Board of Jämtland for the permission to sample trees in Vålådalen nature reserve. We also thank Jesper Björklund and Kristina Seftigen for assistance in the lab.

References

Alexander, M.R., Pearl, J.K., Bishop, D.A., Cook, E.R., Anchukaitis, K.J., Pederson, N., 2019. The potential to strengthen temperature reconstructions in ecoregions with limited tree line using a multispecies approach. Quat. Res. 92, 583–597. https://doi.org/10.1017/qua.2019.33.

Andreassen, K., Solberg, S., Tveito, O.E., Lystad, S.L., 2006. Regional differences in climatic responses of Norway spruce (Picea abies L. Karst) growth in Norway. For. Ecol. Manag. 222, 211–221. https://doi.org/10.1016/j.foreco.2005.10.029.

Biondi, F., Waikul, K., 2004. DENDROCLIM2002: A C+ + program for statistical calibration of climate signals in tree-ring chronologies. Comput. Geosci. 30, 303–311.

Björklund, J., Gunnarson, B.E., Seftigen, K., Esper, J., Linderholm, H.W., 2014. Blue intensity and density from northern Fennoscandian tree rings, exploring the potential to improve summer temperature reconstructions with earlywood information. Clim 10, 877–885. https://doi.org/10.5194/cp-10-877-2014.

Björklund, J., Gunnarson, B.E., Seftigen, K., Zhang, P., Linderholm, H.W., 2015. Using adjusted Blue Intensity data to attain high-quality summer temperature information: a case study from Central Scandinavia. Holocene 25, 547–556. https://doi.org/10.1177/0959683614562434.

Campbell, R., McCarroll, D., Loader, N.J., Grudd, H., Robertson, I., Jalkanen, R., 2007. Blue intensity in Pinus sylvestris tree-rings: developing a new palaeoclimate proxy. Holocene 17 (6), 821–828. https://doi.org/10.1177/0959683607080523.

Castagneri, D., Storaunet, K.O., Rolstad, J., 2013. Age and growth patterns of old Norway spruce trees in Trillemarka forest, Norway. Scand. J. For. Res. 28, 232–240. https://doi.org/10.1080/02827581.2012.724082.

Caudullo, G., Tinner, W. & de Rigo, D. (2016). Picea abies in Europe: distribution, habitat, usage and threats. European Atlas of Forest Tree Species. Publications Office of the European Union, Luxembourg.

Chen, D., Hellström, C., 1999. The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: spatial and temporal variations. Tellus Dyn. Meteorol. Oceanogr. 51, 505–516. v51i4 (14086). https://doi.org/10.3402/tellusa.

Cook, E.R., Briffa, K.R., Meko, D.M., Graybill, D.A., Funkhouser, G., 1995. The "segment length curse" in long tree-ring chronology development for palaeoclimatic studies. Holocene 5 (2), 229–237. https://doi.org/10.1177/095968369500500211.

Cook, E.R., and Krusic, P.J., (2005). Program ARSTAN: a Tree-ring Standardization Program Based on Detrending and Autoregressive Time Series Modeling, with Interactive Graphics. Lamont-Doherty Earth Obs. Columbia Univ., Palisades NY.

Cook, E.R., Peters, K., 1981. The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. Tree-Ring Bull. 41, 45–53.

Cybis, (2016). Check your blue intensity calibration with CooRecorder 8.1. Accessed 2022-02-10 ⟨https://www.cybis.se/forfun/dendro/helpcoorecorder7/⟩.

Durrant, T. de Rigo, D. Caudullo, G. (2016). Pinus sylvestris in Europe: distribution, habitat, usage and threats. European Atlas of Forest Tree Species. Publications Office of the European Union, Luxembourg.

Esper, J., Düthorn, E., Krusic, P., Timonen, M., Büntgen, U., 2014. Northern European summer temperature variations over the Common Era from integrated tree-ring density records. J. Quat. Sci. 29, 487–494. https://doi.org/10.1002/jqs.2726.

Folland, C.K., Knight, J., Linderholm, H.W., Fereday, D., Ineson, S., Hurrell, J.W., 2009. The summer north atlantic oscillation: past, present, and future. J. Clim. 22 (5), 1082–1103. https://doi.org/10.1175/2008JCLI2459.1.

Frank, D., Esper, J., 2005. Characterization and climate response patterns of a high-elevation, multi-species tree-ring network in the European Alps. Dendrochronologia 22, 107–121. https://doi.org/10.1016/j.dendro.2005.02.004.

Franke, J., Frank, D., Raible, C., Esper, J., Brönnimann, S., 2013. Spectral biases in tree-ring climate proxies. Nat. Clim. Change 3, 360–364. https://doi.org/10.1038/nclimate1816.

Fritts, H.C. (1976). Tree-rings and climate, Academic Press, Great Britain.

Fuentes, M., Salo, R., Björklund, J., Seftigen, K., Zhang, P., Gunnarson, B., Aravena, J.-C., Linderholm, H.W., 2018. A 970-year-long summer temperature reconstruction from Rogen, west-central Sweden, based on blue intensity from tree rings. Holocene 28 (2), 254–266. https://doi.org/10.1177/0959683617721322.

Gagen, M., Zorita, E., McCarroll, D., Young, G.H.F., Grudd, H., Jalkanen, R., Loader, N.J., Robertson, I., Kirchhefer, A., 2011. Cloud response to summer temperatures in Fennoscandia over the last thousand years. L05701 Geophys. Res. Lett. 38. https://doi.org/10.1029/2010GL046216.

Gunnarson, B., 2008. Temporal distribution pattern of subfossil pines in central Sweden: perspective on Holocene humidity fluctuations. Holocene 18, 569–577. https://doi.org/10.1177/0959683608089211.

Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. PAST: Paleontological Statistics software package for education and data analysis. Palaeontol. Electron. 4 (1), 9.

Harris, I., Osborn, T.J., Jones, P., et al., 2020. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. Sci Data 7, 109. https://doi.org/10.1038/s41597-020-0453-3.

Heeter, K., Harley, G., Gevel, S., White, P., 2019. Blue intensity as a temperature proxy in the eastern United States: a pilot study from a southern disjunct population of Picea rubens (Sarg.). Dendrochronologia 55. https://doi.org/10.1016/j.dendro.2019.04.010.

Heeter, K., Harley, G., Maxwell, J., McGee, J., Matheus, T., 2020. Late summer temperature variability for the Southern Rocky Mountains (USA) since 1735 CE: applying blue light intensity to low-latitude Picea engelmannii Parry ex Engelm. Clim. Change 162, 1–24. https://doi.org/10.1007/s10584-020-02772-9.

Heeter, K., Harley, G., Maxwell, J., Wilson, R., Abatzoglou, J., Rayback, S., Rochner, M., Kitchens, K., 2021. Summer temperature variability since 1730 CE across the low-to-mid latitudes of western North America from a tree ring blue intensity network. Quat. Sci. Rev. 267. https://doi.org/10.1016/j.quascirev.2021.107064.

Holmes, R.L., 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull. 43, 69–78. ISSN. 0041-2198.

Jones, P., Briffa, K., Osborn, T., Lough, J., van Ommen, T., Vinther, B., Luterbacher, J., Wahl, E., Zwiers, F., Mann, M., Schmidt, G., Ammann, C., Buckley, B., Cobb, K., Esper, J., Goosse, H., Graham, N., Jansen, E., Kiefer, T., Xoplaki, E., 2009. High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects. Holocene 19, 3–49. https://doi.org/10.1177/0959683608098952.

Kaczka, R.J., Spyt, B., Janecka, K., Beil, I., Büntgen, U., Scharnweber, T., Nievergelt, D., Wilmking, M., 2018. Different maximum latewood density and blue intensity measurements techniques reveal similar results. Dendrochronologia 49 (2018), 94–101. https://doi.org/10.1016/j.dendro.2018.03.005.

Kaczka, R.J., Wilson, R., 2021. I-BIND: international blue intensity network development working group. Dendrochronologia 68, 125859. https://doi.org/10.1016/j.dendro.2021.125859.

Linderholm, H.W., Björklund, J., Seftigen, K., Gunnarson, B., Grudd, H., Jeong, J.-H., Drobyshev, I., Liu, Y., 2010. Dendroclimatology in Fennoscandia - From past accomplishments to future potential. Climate 6, 93–114. https://doi.org/10.5194/cp-6-93-2010.

Linderholm, H.W., Gunnarson, B.E., 2005. Summer temperature variability in central Scandinavia during the last 3600 years. Geogr. Ann.: Ser. A, Phys. Geogr. 87, 231–241. https://doi.org/10.1111/j.0435-3676.2005.00255.x.

Linderholm, H.W., Gunnarson, B., 2019. Were medieval warm-season temperatures in Jämtland, central Scandinavian Mountains, lower than previously estimated? Dendrochronologia 57, 125607. https://doi.org/10.1016/j.dendro.2019.125607.

Linderholm, H.W., Zhang, P., Gunnarson, B., Björklund, J., Farahat, E., Fuentes, M., Rocha, E., Salo, R., Seftigen, K., Stridbeck, P., Liu, Y., 2014. Growth dynamics of tree-line and lake-shore Scots pine (Pinus sylvestris L.) in the central Scandinavian Mountains during the Medieval Climate Anomaly and the early Little Ice Age. Front. Ecol. Evol. 2, 20. https://doi.org/10.3389/fevo.2014.00020.

Lücke, L., Hegerl, G., Schurer, A., Wilson, R., 2019. Effects of Memory Biases on Variability of Temperature Reconstructions. J. Clim. 32, 8713–8731. https://doi.org/10.1175/JCLI-D-19-0184.1.

Lundqvist, J., (1969). Beskrivning till jordartskarta över Jämtlands län. Svenska reproduktions AB (distr.).

Mäkinen, H., Nöjd, P., Kahle, H.-P., Neumann, U., Tveite, B., Mielikäinen, K., Röhle, H., Spiecker, H., 2002. Radial growth variation of Norway spruce (Picea abies (L.) Karst.) across latitudinal and altitudinal gradients in central and northern Europe. For. Ecol. Manag. 171, 243–259. https://doi.org/10.1016/S0378-1127(01)00786-1.

Mäkinen, H., Nöjd, P., Kahle, H.-P., Neumann, U., Tveite, B., Mielikäinen, K., Röhle, H., Spiecker, H., 2003. Large-scale climatic variability and radial increment variation of Picea abies (L.) Karst. in central and northern Europe. Trees 17, 173–184. https://doi.org/10.1007/s00468-002-0220-4.

Maxwell, J.T., Harley, G.L., Matheus, T.J., 2015. Dendroclimatic reconstructions from multiple co-occurring species: a case study from an old-growth deciduous forest in Indiana, USA. Int. J. Climatol. 35, 860–870. https://doi.org/10.1002/joc.4021.

McCarroll, D., Loader, N.J., Jalkanen, R., Gagen, M.H., Grudd, H., Gunnarson, B.E., Kirchhefer, A.J., Friedrich, M., Linderholm, H.W., Lindholm, M., Boettger, T., Los, S. O., Remmele, S., Kononov, Y.M., Yamazaki, Y.H., Young, G.H., Zorita, E., 2013. A 1200-year multiproxy record of tree growth and summer temperature at the northern pine forest limit of Europe. Holocene 23 (4), 471–484. https://doi.org/10.1177/0959683612467483.

McCarroll, D., Pettigrew, E., Luckman, A., Guibal, F., Edouard, J.-L., 2002. Blue reflectance provides a surrogate for latewood density of high-latitude pine tree rings. Arct., Antarct., Alp. Res. 34 (4), 450–453. https://doi.org/10.2307/1552203.

National Research Council. (2006). Surface Temperature Reconstructions for the Last 2,000 Years. Washington, DC: The National Academies Press. https://doi.org/10.17226/11676.

PAGES2k Consortium, 2017. A global multiproxy database for temperature reconstruction of the common era. Sci. Data 4, 170088. https://doi.org/10.1038/sdata.2017.88.

Rocha, E., Gunnarson, B., Björklund, J., Zhang, P., Linderholm, H.W., (2021) A Norway spruce tree-ring width chronology for the Common Era from the Central Scandinavian Mountains, Dendrochronologia, Volume 70, 125896, ISSN 1125-7865, ⟨https://doi.org/10.1016/j.dendro.2021.125896⟩.

Rydval, M., Larsson, L., Mcglynn, L., Gunnarson, B., Loader, N., Young, G., Wilson, R., 2014. Blue Intensity for Dendroclimatology: should we have the blues? Experiments

from Scotland. Dendrochronologia 32. https://doi.org/10.1016/j.dendro.2014.04.003.
Salmela, M.J., Cavers, S., Cottrell, J.E., Iason, G.R., Ennos, R.A., 2013. Spring phenology shows genetic variation among and within populations in seedlings of Scots pine (*Pinus sylvestris* L.) in the Scottish Highlands. Plant Ecol. Divers. 6 (3–4), 523–536. https://doi.org/10.1080/17550874.2013.795627.
Schweingruber, F.H., Fritts, H.C., Bräker, O.U., Drew, L.G., Schär, E., 1978. The x-ray technique as applied to dendrochronology. Tree-ring Bull. 38, 61–91.
Seftigen, K., Cook, E.R., Linderholm, H.W., Fuentes, M., Björklund, J., 2015. The potential of deriving tree-ring-based field reconstructions of droughts and pluvials over Fennoscandia. J. Clim. 28, 3453–3471. https://doi.org/10.1175/JCLI-D-13-00734.1.
Seftigen, K., Fuentes, M., Ljungqvist, F.C., Björklund, J., 2020. Using Blue Intensity from drought-sensitive *Pinus sylvestris* in Fennoscandia to improve reconstruction of past hydroclimate variability. Clim. Dyn. 55 (2020), 579–594. https://doi.org/10.1007/s00382-020-05287-2.
Seftigen, K., Linderholm, H.W., Loader, N., Liu, Y., Young, G., 2011. The influence of climate on 13C/12C and 18O/16O ratios in tree ring cellulose of *Pinus sylvestris* L. growing in the central Scandinavian Mountains. Chem. Geol. 286, 84–93. https://doi.org/10.1016/j.chemgeo.2011.04.006.
Semenyak, N., Dolgova, E., 2023. Dendroclimatic signals in the pine and spruce chronologies in the Solovetsky Archipelago. Dendrochronologia 77, 126029. https://doi.org/10.1016/j.dendro.2022.126029.
SMHI, (2022). Ladda ner meteorologiska observationer. Accessed 2022-02-09 at: ⟨https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer#param=airtemperatureInstant,stations=all,stationid= 132620⟩.
Snee, R.D., 1977. Validation of regression models: methods and examples. Technometrics 19 (4), 415–428. https://doi.org/10.2307/1267881.
St. George, S., 2014. An overview of tree-ring width records across the Northern Hemisphere. Quat. Sci. Rev. 95, 132–150. https://doi.org/10.1016/j.quascirev.2014.04.029.
Stokes, M.A., Smiley, T.L., (1996). An Introduction to Tree-Ring Dating, second ed. University of Arizona Press, Tucson.
Storaunet, K.O., Rolstad, J., 2002. Time since death and fall of Norway spruce logs in old-growth and selectively cut boreal forest. Can. J. For. Res. 32, 1801–1812. https://doi.org/10.1139/x02-105.
Stridbeck, P., Björklund, J., Fuentes, M., Gunnarson, B.E., Jönsson, A.M., Linderholm, H.W., Charpentier, F., Olsson, C., Rayner, D., Rocha, E., Zhang, P., Seftigen, K., 2022. Dendrochronologia 75, 125993. https://doi.org/10.1016/j.dendro.2022.125993.
Trachsel, M., Kamenik, C., Grosjean, M., Mccarroll, D., Moberg, A., Brázdil, R., Büntgen, U., Dobrovolny, P., Esper, J., Frank, D., Friedrich, M., Glaser, R., Larocque-Tobler, I., Nicolussi, K., Riemann, D., 2012. Multi-archive summer temperature reconstruction for the European Alps, AD 1053–1996. Quat. Sci. Rev. 46, 66–79. https://doi.org/10.1016/j.quascirev.2012.04.021.
Trouet, V., Oldenborgh, G.J.V., 2013. KNMI climate explorer: a web-based research tool for high-resolution paleoclimatology. Tree Ring Res 69, 3–13. https://doi.org/10.3959/1536-1098-69.1.3.
van der Maaten-Theunissen, M., Kahle, H.-P., van der Maaten, E., 2013. Drought sensitivity of Norway spruce is higher than that of silver fir along an altitudinal gradient in southwestern Germany. Ann. For. Sci. 70, 185–193. https://doi.org/10.1007/s13595-012-0241-0.
Wigley, T.M., Briffa, K.R., Jones, P.D., 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. J. Appl. Meteorol. Climatol. 23, 201–213. https://doi.org/10.1175/1520-0450(1984)023< 0201:OTAVOC> 2.0.CO;2.
Wilson, R., Anchukaitis, K., Andreu-Hayles, L., Cook, E., D'Arrigo, R., Davi, N., Haberbauer, L., Krusic, P., Luckman, B., Morimoto, D., Oelkers, R., Wiles, G., Wood, C., 2019. Improved dendroclimatic calibration using blue intensity in the southern Yukon. Holocene 29 (11), 1817–1830. https://doi.org/10.1177/0959683619862037.
Wilson, R., Rao, R., Rydval, M., Wood, C., Larsson, L.-Å., Luckman, B.H., 2014. Blue Intensity for dendroclimatology: The BC blues: a case study from British Columbia, Canada. Holocene 24 (11), 1428–1438. https://doi.org/10.1177/0959683614544051.
Zhang, P., Linderholm, H.W., Gunnarson, B.E., Björklund, J., Chen, D., 2016. 1200 years of warm-season temperature variability in central Scandinavia inferred from tree-ring density. Clim 12, 1297–1312. https://doi.org/10.5194/cp-12-1297-2016.