Blue intensity in *Pinus sylvestris* tree-rings: developing a new palaeoclimate proxy

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Abstract: Minimum blue intensity measurements of resin-extracted *Pinus sylvestris* (L.) samples, conducted using a flat-bed scanner and commercially available software, are shown to provide a robust and reliable surrogate for maximum latewood density. Blue intensity data from 15 trees, from three stands, are reported relative to a standard blue-scale in a manner similar to grey-scale calibration in x-ray densitometry. The resulting time series are highly correlated with x-ray densitometry data generated from the same samples and preserve the same high level of signal strength. Sensitivity to summer climate variables is similar to that identified in the relative density record, demonstrating that minimum blue intensity can also be used for the study of climate change. While not a replacement for the powerful range of x-ray densitometry techniques, blue intensity provides an inexpensive and accessible alternative for accessing palaeoclimatic information.

Key words: Reflected light image analysis, blue intensity, dendrochronology, dendroclimatology, Scots pine, relative density, tree line, palaeoclimate.

Introduction

Environmental influences during wood formation can directly control the physical and chemical properties of tree-rings. Absolutely dated tree-ring chronologies have been developed that extend over centuries or even millennia and provide an important archive for evaluating both past and current natural climate variability (Eronen *et al.*, 2002; Grudd *et al.*, 2002; McCarroll *et al.*, 2003; Laroque and Smith, 2005).

To access this archive a wide range of physical and chemical proxies of palaeoclimate have been studied; including radial growth, maximum latewood density, stable isotopes and reflected light image analysis (Briffa *et al.*, 2002; Grudd *et al.*, 2002; McCarroll *et al.*, 2002; Loader *et al.*, 2003; McCarroll and Loader, 2004). Maximum latewood density in particular has proven a valuable proxy in coniferous tree-line species, and can provide a very strong palaeoclimate signal, even in areas where ring widths exhibit little variation (Parker and Henoch, 1971). X-ray densitometry has been used to reconstruct temperature during the growing season at cool, moist sites (Briffa *et al.*, 1988) and precipitation at drier sites (Cleaveland, 1986), as well as for identifying wood properties such as juvenile wood (Sauter *et al.*, 1999), early/latewood proportions and compression wood (Seth and Jain, 1978; Lenz *et al.*, 1976). However, extracting relative density information from tree-rings using this approach has been hindered historically by analytical procedures that were too time-consuming and costly for many tree-ring laboratories (González and Eckstein, 2003; Silkin and Kirdyanov, 2003; Sarén *et al.*, 2004).

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Recent advances in image-analysis techniques have enabled an unprecedented evaluation of wood properties and ring growth variables at a high resolution (Sheppard *et al.*, 1996; McCarroll *et al.*, 2002; Sheppard and Singavarapu, 2006). However, many of these methods require access to bespoke technologies; exhibit limitations in terms of sample preparation or have a limited range of species to which they can be applied. In a pilot study, McCarroll *et al.* (2002) first demonstrated a close association between minimum blue intensity and maximum latewood density measured on a number of young *Pinus sylvestris* (L.) samples, suggesting that blue intensity behaves as a reliable surrogate for latewood density because it is sensitive to the degree of lignification of the latewood cells. This is supported by earlier wood anatomical studies, which have demonstrated that the lignin content of latewood cell walls is susceptible to the influence of climatic variability (Gindl *et al*., 2000). McCarroll *et al.* (2002) combined a region-growing software algorithm with a reflected blue light image produced using a standard flat-bed scanner. Despite presenting convincing results and proposing blue intensity as an inexpensive surrogate for maximum latewood density, their method has not been widely adopted. This may reflect the specialist nature of the image analysis software used and/or the relatively short (juvenile) tree-ring series studied, which prevented investigation of signal preservation or climate sensitivity over longer timescales.

Here we modify and advance the blue intensity method by measuring the brightness of the light reflected from laths using a commercially available scanner and software package (WinDENDRO™) that is already widely used in dendrochronology laboratories and relate these results to a scale that allows comparison between laboratories. The new approach is illustrated using samples from three stands of *Pinus sylvestris* trees from northern Finland, allowing us to test the temporal stability of the relationship between x-ray density and blue intensity and between blue intensity and climate parameters.

Materials and methods

Study area

Scots pine (*Pinus sylvestris* L.) trees were sampled from three stands at sites near Laanila in northern Finland (68°30′N, 27°30′E) (220 m a.s.l.). The climate in northeast Fennoscandia is continental subarctic (Andersson *et al*., 1996) with the warmest month in July (+13.1°C in AD 1961–1990) and the coldest months in January and February (−13.7°C in AD 1961–1990). Summer precipitation is between 80 and 289 mm (Ivalo Meteorological Station (AD 1958–2002)). All trees were growing on dry or moist heath that is typical for pine stands in upper Lapland. Breast-height discs were collected from five Scots pine trees from each stand (*n* = 15 trees), based on dominance, and were visually assessed to be healthy with straight, unbroken stems and regular-shaped crowns.

Laboratory analysis

To provide a direct comparison of both methods, the same thin laths of wood were analysed for both the blue intensity and x-ray densitometry. Thirty radii from a total of 15 living pine trees were collected for measurement. Samples were prepared according to the protocols of Schweingruber *et al.* (1988). Radii were cut perpendicular to the direction of the fibres into laths 1.25 mm thick, using a twin-blade circular saw. The laths were chemically treated, by an ethanol Soxhlet extraction, to remove resins and extractives (Schweingruber *et al.*, 1978). The samples were cut, pre-treated, x-rayed and latewood density was measured in the Department of Physical Geography and Quaternary Geology, Stockholm University using an Itrax density scanner (see Bergsten *et al*., 2001). In this comparison of methods, no further processing or surfacing was carried out.

Intensity data were collected by scanning the 30 wooden laths using an Epson Expression 1680 flatbed Pro Series line scanner and SilverFast Ai professional scan software. The images were scanned at a resolution of 1000 dpi and saved as >24 –48 bit colour images. The image analysis software permits the user to select which channels (true grey, red, green, blue or composite red, green, blue (RGB)) of a scanned image are enabled for visualization and analysis. Based on previous work (McCarroll *et al*., 2002), the blue channel was enabled as it most faithfully tracked the maximum latewood density signal. This integrated all pertinent picture elements into a brightness scan ranging from white (full range RGB = 255) to black (full range RGB = 0). Blue intensity measurements were carried out in the Department of Geography, at Swansea University.

To enable the comparison of latewood density and blue intensity values determined in different laboratories, the measurements were calibrated. In the measurement of latewood density a cellulose acetate calibration wedge of known density and with steps of known thickness was x-rayed. WinDENDRO uses this calibration to translate greyscale brightness values into density units (g/cm^3). Equivalent calibration of blue intensity requires a series of steps of known colour within the blue scale, and this can be provided using a standard Monaco EZ-colour card (monr2004:08–01 version 2). The colour card was scanned in the same way as the wood laths. Eight steps were selected; six from within the blue colour tones and one black and one white step (Figure 1) in a similar manner to the example of the density 'gradient' presented here. To reduce measurement error this initial calibration procedure was repeated 15 times and confidence parameters were calculated ($p < 0.05$). The calibration step in WinDENDRO is designed to deal with material densities rather than colour differences, however, harmonization of the reflected light image to a common and consistent standard and its subsequent division into an eight step 'gradient' of intensity, saturation and hue provides a means by which both samples and systems can objectively be compared and calibrated.

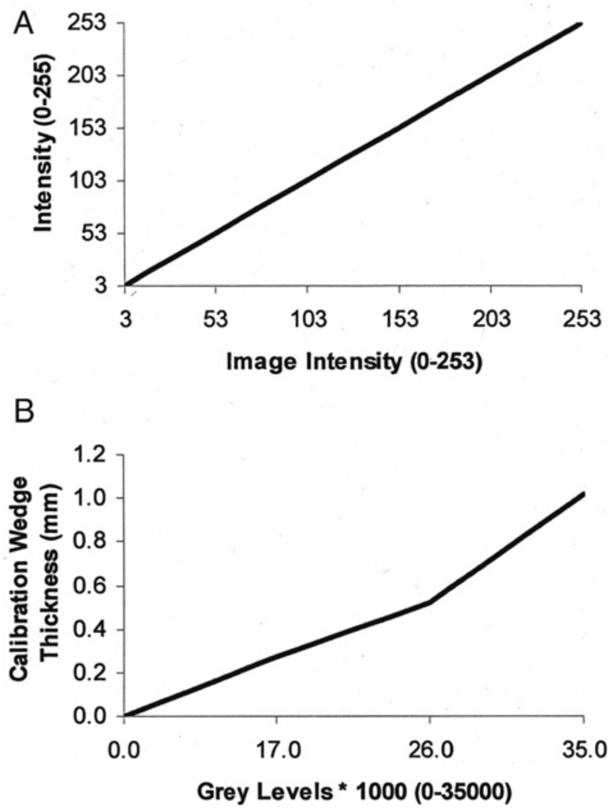

Figure 1 Graphical representation of light calibration parameters (black line) for (A) blue intensity measures (0–253 blue tones) and (B) an example of maximum latewood density (0–35000 levels)

When WinDENDRO is used in the measurement of the x-ray relative density of tree cores, a line of sensors is traced along a profile, crossing each ring boundary at right angles. The resulting profile of maximum and minimum density and the mean densities of the earlywood, latewood and of the whole ring are recorded. Maximum density, which occurs in the latewood, has proved one of the most valuable proxies for palaeoclimate studies (McCarroll *et al*., 2003). For analysis of tree-ring blue intensity the measurement process is similar. WinDENDRO measures the brightness of the reflected light from the laths and the resulting profile of maximum and minimum brightness and the mean brightness of the earlywood, latewood and of the whole ring are recorded. Minimum brightness (in the blue band of the image), which occurs in the latewood, was identified by McCarroll *et al.* (2002) as a surrogate for maximum latewood density. Based upon these earlier findings, this parameter was also selected in this comparative study. For each ring, the mean of this mini-mum intensity value was calculated from three measurements. Cross-dating was accomplished using the software COFECHA (Holmes, 1999), which also describes some of the statistical properties of the data (Table 1).

The year-to-year growth pattern in trees is usually governed by the annual variation in climate, but on longer timescales, slowly evolving biological and environmental factors are imparted to this climatic forcing. Hence, tree-ring series are commonly treated with a filtering technique known as 'standardization', designed to remove unwanted 'noise' or trends in the data series, leaving the signal of interest. The computer program ARSTAN (Cook and Holmes, 1986) was used to produce standardized latewood density and blue intensity indices, using a single-step process where either a negative exponential or linear curve de-trending was applied. Indices for all chronologies were produced by subtraction (Cook and Kairiukstis, 1990) (Table 2).

Simple correlations were calculated to identify significant correlation coefficients related to climate parameters (Table 3) recorded at the meteorological station at Ivalo (AD 1958–2002), which is located 12 km north of Laanila and with the more distant (130 km south) but longer temperature record from Sodankylä (AD 1908–2002). The latewood density and blue intensity time series were compared statistically and their response to climate series were compared with monthly mean temperature, total monthly precipitation, total monthly sunshine, temperature, mean monthly relative humidity and growing season temperatures (June, July, August (JJA)) variables.

Table 1 Raw site chronology statistics for maximum latewood density (MXD) and minimum blue intensity (BLUE) of *Pinus sylvestris* from sites near Laanila, Finland

Cohort	Method	Chronology coverage (AD)	Years	Mean interseries correlation	Mean sensitivity	Autocorrelation	EPS[a]	Correlation coefficient[b]
1	BLUE	1962–2002	41	0.63	0.15	0.43	0.89	–0.90
	MXD			0.71	0.14	0.37	0.92	
2	BLUE	1957–2002	46	0.74	0.17	0.65	0.93	–0.95
	MXD			0.64	0.14	0.59	0.90	
3	BLUE	1777–2002	226	0.61	0.17	0.55	0.89	–0.85
	MXD			0.75	0.16	0.48	0.94	
Mean	BLUE	1777–2002[c]	226	0.60	0.17	0.55	0.88	–0.87
	MXD			0.73	0.15	0.48	0.93	

[a] Expressed population signal.
[b] Pearson correlation coefficient of maximum latewood density and blue intensity chronologies.
[c] Mean chronology comprising all 15 trees (30 radii).

Table 2 Detrended site chronology statistics for maximum latewood density (MXD) and minimum blue intensity (BLUE) index chronologies of *Pinus sylvestris* from sites near Laanila, Finland

Cohort	Method	Chronology coverage (AD)	Years	Mean interseries correlation	Mean sensitivity	Autocorrelation	EPS[a]	Correlation coefficient[b]
1	BLUE	1962–2002	41	0.81	0.15	0.39	0.96	–0.88
	MXD			0.73	0.13	0.31	0.93	
2	BLUE	1957–2002	46	0.75	0.17	0.61	0.94	–0.94
	MXD			0.74	0.14	0.55	0.93	
3	BLUE	1777–2002	226	0.78	0.17	0.54	0.95	–0.85
	MXD			0.69	0.16	0.47	0.92	
Mean	BLUE	1777–2002[b]	226	0.74	0.16	0.52	0.94	–0.84
	MXD			0.72	0.14	0.44	0.93	

[a] Expressed population signal.
[b] Pearson correlation coefficient of maximum latewood density and blue intensity chronologies.
[c] Mean chronology comprising all 15 trees (30 radii).

Table 3 Correlation coefficients identifying the strength of the relationship of mean summer (June, July, August) temperatures, precipitation, sunshine hours and relative humidity (AD 1958–2002) collected from the Ivalo station, Finland and maximum latewood density (MXD) and blue intensity (BLUE) index chronologies of *Pinus sylvestris* from sites near Laanila, Finland

Cohort	Method	Comparison period	Years	Precipitation	Temperature	Sunshine hours	Relative humidity
1	BLUE	1962–2002	41	0.27	–0.75	–0.65	0.49
	MXD		41	–0.41	0.72	0.73	–0.56
2	BLUE	1958–2002	45	0.25	–0.74	–0.67	0.53
	MXD		45	–0.36	0.66	0.68	–0.56
3	BLUE	1958–2002	45	0.37	–0.69	–0.60	0.53
	MXD		45	–0.35	0.57	0.51	–0.51
Mean	BLUE	1958–2002[a]	45	0.29	–0.79	–0.70	0.54
	MXD		45	–0.24	0.61	0.54	–0.55

[a] Mean chronology comprising all 15 trees (30 radii).

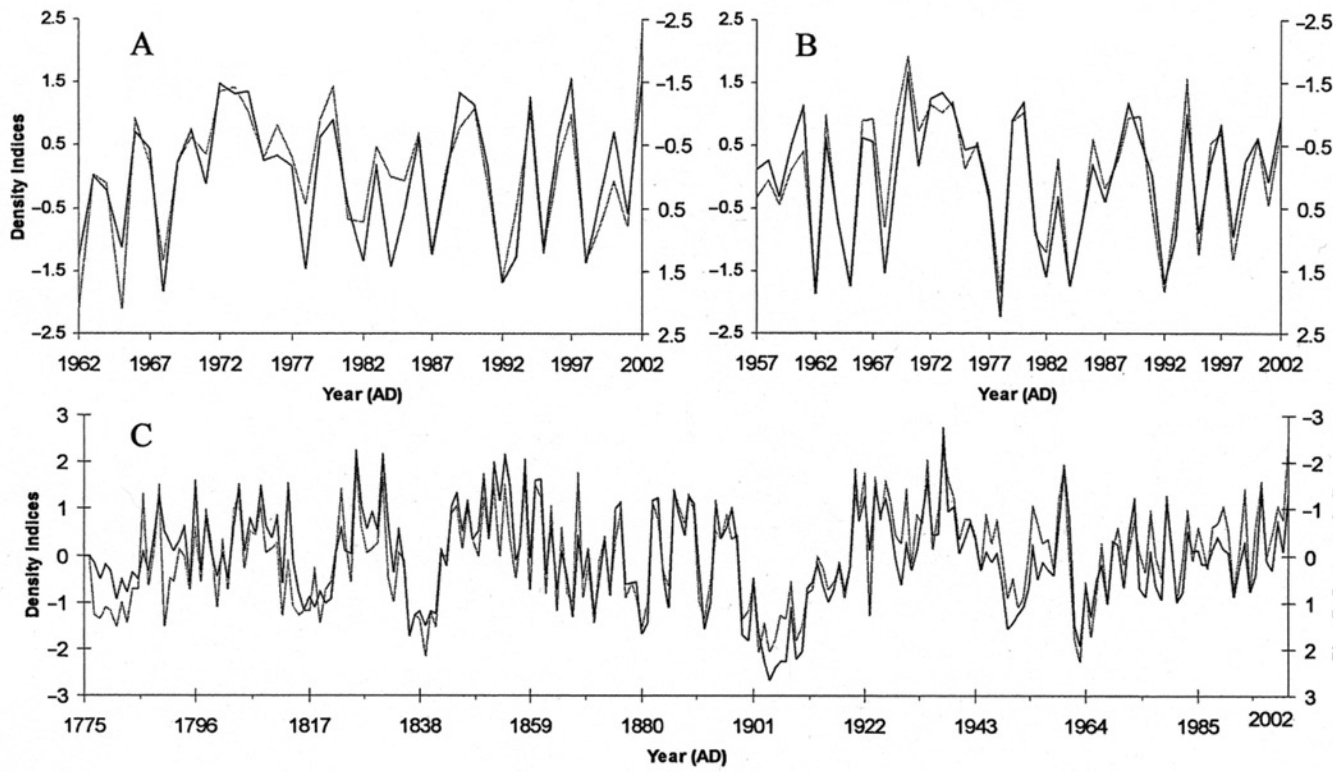

Figure 2 Detrended indices of maximum latewood density (grey line) and minimum blue intensity (black line) for (A) 41 year age (B) 46 year age and (C) 226 year age cohorts of *Pinus sylvestris* from sites near Laanila, Finland

Results and discussion

Signal strength

Scots pine (15 trees, 30 radii) site chronologies were developed from three stands using standard dendrochronological techniques (Fritts, 1976). For the raw, (non de-trended data) the mean inter-series correlation, describing the average pair-wise correlations was calculated for each of the three blue intensity chronologies and ranged from 0.61 to 0.74; similar to those for maximum density 0.64 to 0.75 (Table 1), but sufficiently high to yield Expressed Population Signals (EPS) of 0.89 to 0.93 higher than the generally accepted threshold value of 0.85 (Wigley *et al.*, 1984). Serial auto-correlation, which indicates the degree of relationship between successive values within each time series, is higher for blue intensity than for maximum density (Table 1). However, when the series are de-trended, mean interseries correlations of the blue intensity chronologies increase, so that the EPS values are higher than those obtained for de-trended maximum density (Table 2, Figure 2). The negative correlation between maximum density and blue intensity is slightly weaker after the series have been de-trended, with all three sites yielding correlations >0.85 and an overall correlation of 0.84 (Figure 3).

Climate signal

Blue intensity and latewood density measures were found to respond in a similar way to climate (Table 3), both having similar correlations with various climate variables (Figure 4). The strongest correlation in both cases was with the mean monthly temperature of June to August (Figure 4) and the mean summer seasonal temperature JJA (Figures 5 and 6), with blue intensity giving higher values

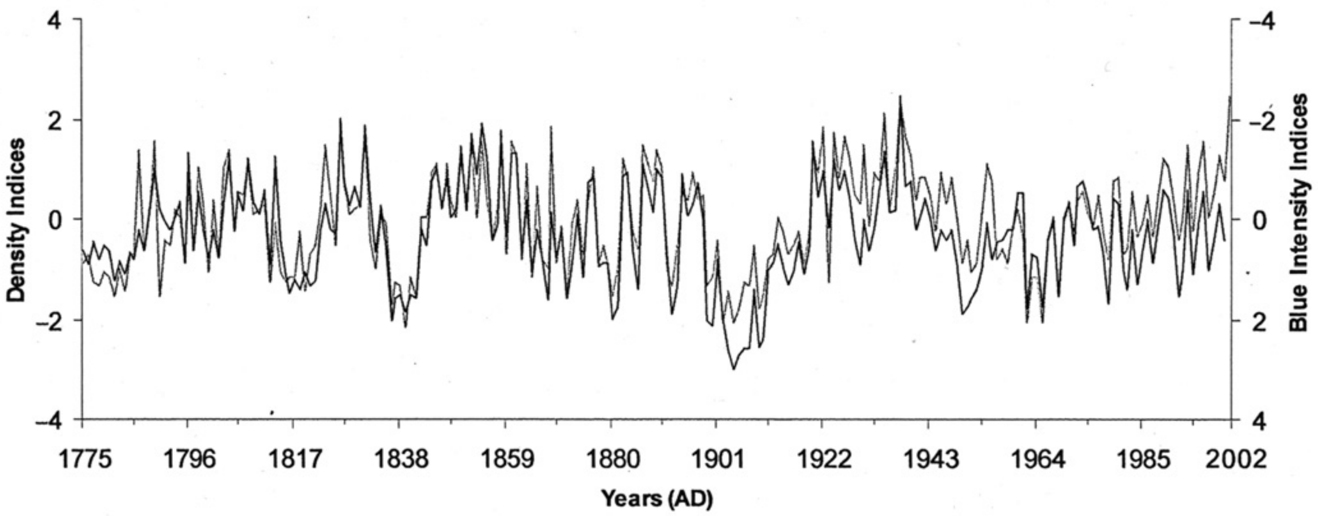

Figure 3 Mean detrended indices of maximum latewood density (grey line) and minimum blue intensity (black line) of *Pinus sylvestris* from sites near Laanila, Finland (n = 15 trees)

than maximum density. For the short Ivalo record the correlation with minimum blue intensity was −0.80, compared with 0.59 for the maximum latewood density (n = 45) (Figure 5); for the longer Sodankylä record the values are −0.65 and 0.58 (n = 91) for blue intensity and relative density respectively (Figure 6). The strong positive correlation between maximum latewood density and summer (June, July, August) mean temperature and sunshine hours agrees well with the findings of McCarroll *et al.* (2003) who suggest that it represents a proxy measure of net photosynthesis over the growing season. Maximum density and minimum blue intensity are strongly correlated because they both reflect, to differing degrees, the lignin content of the latewood cell walls (McCarroll *et al*., 2002). Lignification of the cell wall completes the maturation of a tracheid, so that when favourable conditions lead to a longer

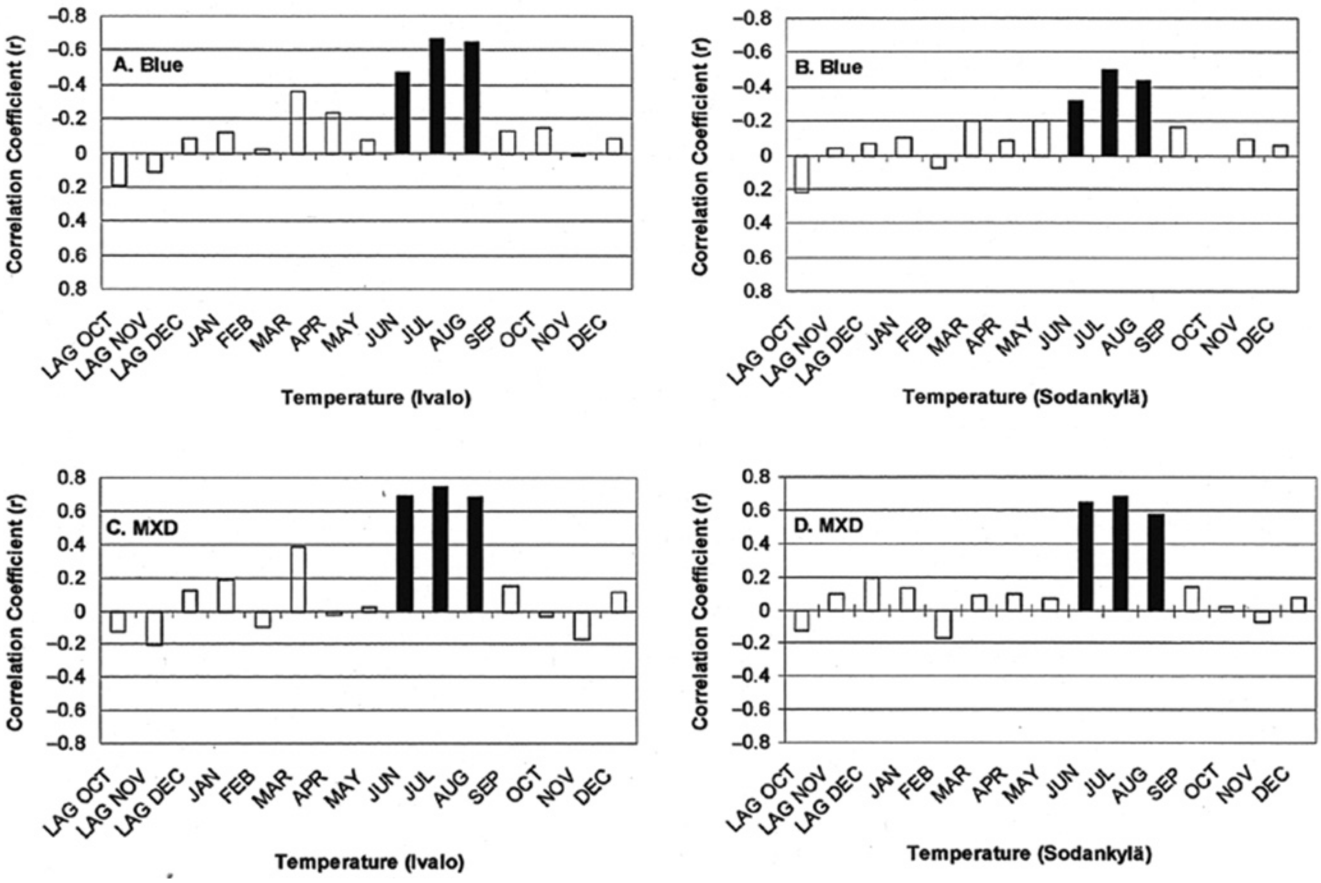

Figure 4 Significant correlation coefficients related to monthly climate parameters from Ivalo and Sodankylä climate stations, Finland for the blue intensity (A, B) and maximum latewood density (C, D) indices of *Pinus sylvestris*. Black bars $p < 0.05$

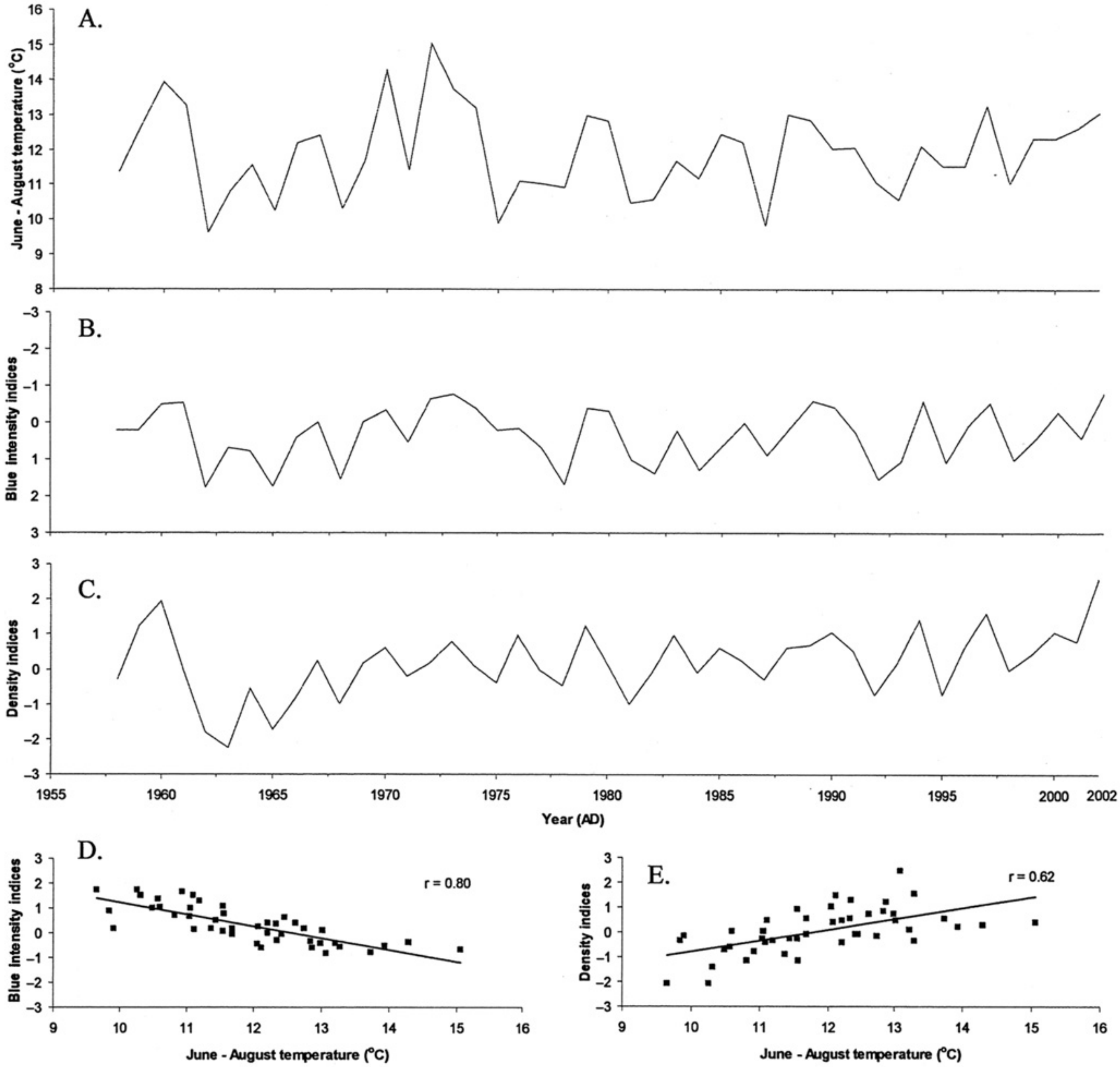

Figure 5 The relationships between June–August temperature from Ivalo station, Finland (AD 1958–2002) (A), and blue intensity (B) and maximum latewood density (C) indices of *Pinus sylvestris* from sites near Laanila, Finland. Correlation of June–August temperature and blue intensity (D) and latewood maximum density (E)

growing season, this is reflected in higher lignin content in the secondary cell wall layer (Gindl *et al.,* 2000).

Conclusions

Minimum blue intensity measurements of resin extracted Scots pine laths provide a robust and reliable surrogate for maximum density because both density and blue intensity are sensitive to the amount of lignin present in the latewood. The approach adopted here builds upon the work of McCarroll *et al.* (2002) but avoids reliance on specialist image analysis software by utilizing commercial software routinely used in many dendrochronology laboratories. A standard calibration procedure is proposed so that the results from different scanners and laboratories will be comparable. The technique is shown to work well for both young and mature Scots pine trees.

Both x-ray densitometry and blue intensity require chemical treatment of thin wood laths, to remove resins and other mobile substances, and the data must be standardized to remove age trends. Our evidence suggests that, after such treatment, blue intensity may preserve an even stronger record of palaeoclimate than maximum density although we recognize that the precise nature of the forcing mechanisms for these two proxies, although similar, may differ.

Blue intensity is not a replacement for the powerful range of x-ray densitometry techniques, but it does provide an inexpensive and accessible alternative that may be used to rapidly access palaeoclimatic information or to pre-screen trees prior to more detailed physical or chemical analyses.

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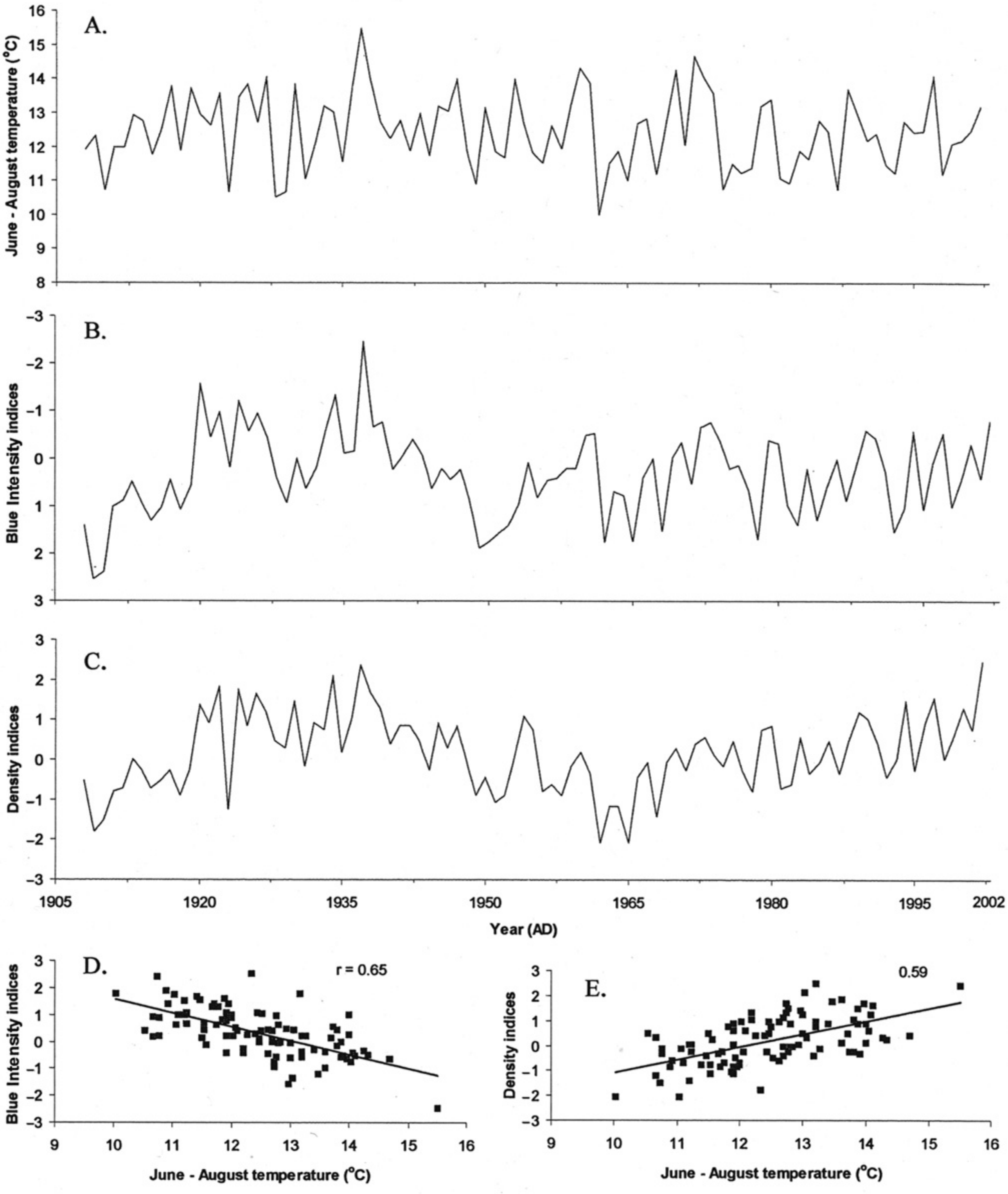

Figure 6 The relationships between June–August temperature from Sodankylä station, Finland (AD 1912–2002) (A), and blue intensity (B) and maximum latewood density (C) indices of *Pinus sylvestris* from sites near Laanila, Finland. Correlation of June–August temperature and blue intensity (D) and latewood maximum density (E)

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