

# Intra-annual dendroclimatic reconstruction for northern British Columbia, Canada, using wood properties

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## Abstract

**Key message** Analyses of tree-ring wood properties combined with an understanding of tree physiology provided detailed intra-annual insights into historical and seasonal climate phenomena in sub-boreal forests of northern British Columbia.

**Abstract** This study investigated historical climate trends in northern British Columbia, Canada, through the use of tree-ring proxies, and established a means of reconstructing intra-annual climate patterns from wood density, fibre properties and tree-ring width data. Specific attention was given to investigating how dendroclimatological analyses of intra-ring wood and fibre properties could be interpreted to improve the strength of proxy climate records. Trees were sampled at six sites in northern British Columbia. Spruce trees were collected from the Smithers area, whilst Douglas-fir trees were sampled at the northern latitudinal extent of their range near Babine and Francois Lakes, and at a precipitation-limited site near Valemount. Wood cores were analysed by Windendro<sup>®</sup> software with an ITRAX scanning densitometer, and by the SilviScan system located at the Australian Commonwealth Scientific and Research Organization. A mean June temperature proxy record dating to 1805 and a July–August mean temperature proxy record for Smithers extending from 1791 to 2006 were constructed from spruce ring width and maximum density chronologies. Douglas-fir ring width, spruce minimum

density, and Douglas-fir maximum cell-wall thickness chronologies were used to reconstruct a May–June precipitation record extending from 1820 to 2006, and a July–August total precipitation record for Fort St. James that extends from 1912 to 2006. The results of the study demonstrate that a combination of multivariate and single-variate analyses provide detailed insights into seasonal radial growth characteristics. Tree physiological responses to climate at different times throughout the growing season, and temperature and precipitation fluctuations over the historical record are discussed.

**Keywords** Dendroclimatology · Fibre properties · Temperature · Precipitation · Tree physiology

## Introduction

The impact of ongoing climate changes on the boreal and sub-boreal forests of northern Canada is expected to be profound and certain to influence their future productivity (Soja et al. 2007; McLane et al. 2011). The boreal forests of northernmost British Columbia are located within a region predominantly influenced by a continental climatic regime characterised by temperature extremes and long, cold winters. Immediately to the south, the sub-boreal forests of north-central British Columbia experience similar climates, but with less seasonal variation in temperature and greater amounts of precipitation. Both regions have dense forests of hybrid white spruce [*Picea glauca* (Moench) Voss *x engelmannii* (Parry)], sub-alpine fir (*Abies lasiocarpa*), black spruce (*Picea mariana*), and lodgepole pine (*Pinus contorta* var. *latifolia*), with scattered Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] stands populating the southern margins of the sub-boreal forest zone (Meidinger 1998).

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The few dendroclimatic studies completed in this region point to summer temperature as the climate variable most responsible for limiting radial growth (Collins et al. 2002; Flower and Smith 2011), with variations in growth response determined by site-specific variables such as elevation and stand dynamics (Lo et al. 2010). Ongoing climate changes in this region have resulted in warmer and wetter summers (Spittlehouse 2009) that have, almost certainly, impacted radial growth behaviour in a manner similar to that experienced in the nearby boreal forests of Alaska and Canada north of 60° (Houghton et al. 2001; Woods et al. 2005; Spittlehouse 2006; Chhin et al. 2008). At some locations, these climate changes have led to fundamental shifts from temperature as the primary limiting factor to growth, to precipitation and/or moisture availability emerging as the factor(s) most responsible for annual incremental growth (Jacoby and D'Arrigo 1995; Porter and Pisaric 2011; Chavardes et al. 2013).

Full understanding of the impact of changed climates on forest growth and productivity in northern British Columbia necessitates the application of innovative dendroclimatological studies to develop an understanding of the intra-annual response of cambium growth, wood density and wood fibre properties. It is expected that this approach will yield more information about tree growth properties, as they relate to the surrounding environment, than has been traditionally available through dendroclimatological studies. Climate may influence all types of tree-ring data, including annual ring width, earlywood and latewood widths, and earlywood and latewood densities, depending on the species and sites investigated (Bouriaud et al. 2005; Fritts 1976). The historical focus of most dendroclimatological applications has been on the construction of inter-annual climate histories through analysis of tree-ring width, with the most robust reconstructions often limited to relationships developed with summer growing season temperatures (Fritts 1976; Kozłowski 1979). Various wood properties within tree rings are, however, known to be sensitive to intra-annual changes in climate (Chen et al. 2010; Schweingruber 2007; Bouriaud et al. 2005; Watson and Luckman 2002; Meko and Baisan 2001) and offer the opportunity to provide high-resolution analyses of climatic variability (i.e. Helama et al. 2012; Xu et al. 2012a, b; Novak 2013). In particular, wood density and finer fibre properties provide a means to reconstruct historical intra-annual climate data, and they have often been shown to correlate more strongly to some climatic factors than ring width (Polge 1970; Parker 1976; Conkey 1986; Woodcock 1989; Schweingruber 1990; D'Arrigo et al. 1992; Wimmer and Grabner 2000; Davi et al. 2002; Drew et al. 2012).

Previous studies using wood proxies in British Columbia have been largely limited to the use of ring width and maximum ring density parameters to construct proxy

temperature records (Watson and Luckman 2001; Davi et al. 2003; Larocque and Smith 2005; Youngblut and Luckman 2008; Flower and Smith 2011; Pitman and Smith 2012; Wood and Smith 2013). The goal of this study was to investigate historical climate trends in northern British Columbia using multiple tree-ring proxies, and to establish a means of reconstructing intra-annual climate patterns from the combined application of wood density, fibre properties, and tree-ring width data. Specific attention was given to investigating how dendroclimatological analyses of intra-ring wood and fibre properties could be interpreted to improve the strength of proxy climate records and to further the understanding of how wood properties are related to climate parameters. It was hypothesised that the use of multiple wood and fibre variables for climate reconstruction would increase the strength and accuracy of the predictions over single-variate models, and that density and fibre properties would correspond more closely with intra-annual variations in climate than annual ring width measurements.

## Materials and methods

### Study sites and climate information

Hybrid spruce and Douglas-fir trees were sampled at six sites in northern British Columbia (Table 1; Fig. 1). The sites contained mixed-species old-growth stands and were located in close proximity to long-term meteorological stations. Well-drained, nutrient-rich sites with open canopy structures were targeted to avoid signal noise caused by site conditions or inter-tree competition. Spruce trees (Sx) were collected from three high-elevation sites in the Smithers area (NSx1, NSx2, NSx3). Douglas-fir (Fd) trees were sampled at the northern latitudinal extent of their range at near Babine and Francois Lakes (NDf4, NDf5), and at a site near Valemount (NDf6) in a precipitation-limited area (Ministry of Environment 2011) (Table 1).

Instrumental climate data were obtained from the Adjusted Historical Canadian Climate Data website (<http://www.cccma.ec.gc.ca/hccd/>) for the Smithers (station #1077500, Lat 54°82'N, Long 127°18'W, 522 m a.s.l.), Fort St. James (station #1092970, Lat 54°45'N, Long 124°25'W, 686 m a.s.l.), and Quesnel (station #1096630, Lat 53° 03'W, Long 122°52'N, 545 m a.s.l.) climate stations (Fig. 1).

### Sampling and preparation

Three cores were collected from each tree sampled using increment borers: two 5.2-mm-diameter cores from opposite sides of individual tree stems, and one 12-mm-diameter

**Table 1** Master chronology statistics for northern British Columbia sample collection sites

Site name	Chronology type	Species	Number of cores (trees)	Site latitude N	Site longitude W	Elevation (m asl)	Chronology length (years AD)	Interseries correlation	Mean sensitivity	EPS cutoff value (years AD)
NSx1	RW	Sx	23 (16)	54° 44.5'	127° 13.9'	890	1598–2006	0.448	0.165	1786
NSx2	RW	Sx	17 (13)	54° 45.9'	127° 16.2'	1430	1680–2006	0.493	0.195	1805
NSx3	RW	Sx	19 (17)	55° 05.7'	127° 13.1'	1100	1726–2006	0.507	0.169	1853
NDf4	RW	Fd	18 (14)	54° 29.9'	125° 23.5'	980	1754–2006	0.500	0.205	1855
NDf5	RW	Fd	16 (16)	54° 02.4'	125° 22.2'	839	1724–2006	0.525	0.212	1820
NDf6	RW	Fd	16 (16)	52° 56.7'	119° 23.2'	803	1728–2006	0.552	0.212	1780
NSx1	MXD	Sx	19 (13)	54° 44.5'	127° 13.9'	890	1610–2006	0.438	0.074	1791
NSx1	MD	Sx	20 (13)	54° 44.5'	127° 13.9'	890	1670–2006	0.465	0.054	None
NSx1	MND	Sx	16 (11)	54° 44.5'	127° 13.9'	890	1670–2006	0.352	0.073	None
NSx2	MXD	Sx	19 (14)	54° 45.9'	127° 16.2'	1430	1716–2006	0.633	0.106	1764
NSx2	MD	Sx	20 (14)	54° 45.9'	127° 16.2'	1430	1716–2006	0.536	0.068	1764
NSx2	MND	Sx	18 (13)	54° 45.9'	127° 16.2'	1430	1716–2006	0.401	0.081	1814
NDf4	MXD	Fd	7 (7)	54° 29.9'	125° 23.5'	980	1810–2006	0.499	0.076	1912
NDf4	MD	Fd	17 (11)	54° 29.9'	125° 23.5'	980	1810–2006	0.461	0.069	1912
NDf4	MND	Fd	14 (9)	54° 29.9'	125° 23.5'	980	1810–2006	0.354	0.077	1970
NSx1 and 2	XCWT	Sx	19 (18)	As listed above	As listed above	As listed above	1686–2006	0.473	0.109	1782
NSx1 and 2	NMFA	Sx	13 (12)	As listed above	As listed above	As listed above	1710–2006	0.364	0.074	None
NDf4	XCWT	Fd	7 (7)	54° 29.9'	125° 23.5'	980	1810–2006	0.474	0.085	1912
NDf4	NMFA	Fd	8 (8)	54° 29.9'	125° 23.5'	980	1810–2006	0.453	0.102	1940

Sx hybrid white spruce, Fd interior Douglas-fir, RW ring width, MD mean ring density, MXD maximum ring density, MND minimum ring density, XCWT maximum cell-wall thickness, NMFA minimum microfibril angle

core collected from directly beneath one of the 5.2-mm core locations. Core position was chosen to minimise effects of slope on the ring patterns and to facilitate optimal cross-dating. The cores were stored in open-ended plastic straws and allowed to air dry.

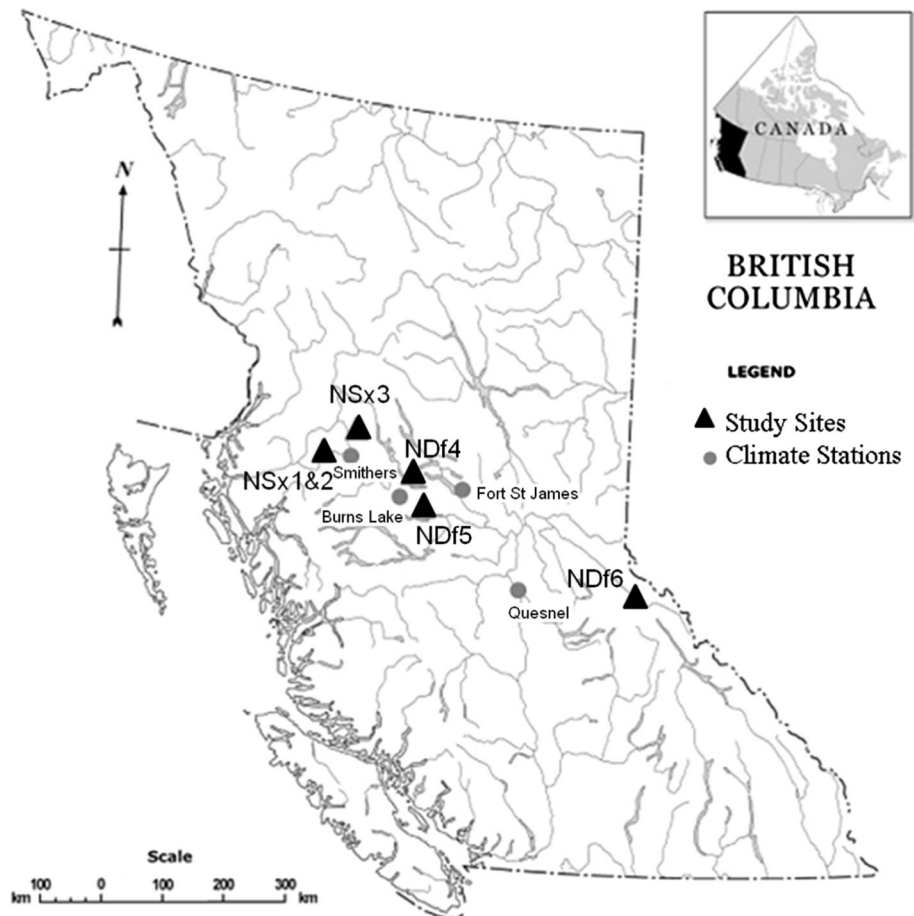
One 5.2-mm core was prepared for ring width analysis using standard dendrochronological techniques (Stokes and Smiley 1968) and the second was prepared for X-ray densitometry. The ring width cores were glued to grooved mounting boards, sanded to a fine polish and scanned with a high-resolution Epson XL 1000 flatbed scanner to create a digital image of each core. The width of each annual ring was measured to 0.001 mm using Windendro® (Version 2006).

The densitometry cores were glued flush to the surface of a 2.5-cm-wide fibreboard block and cut (pith to bark) with a Waltech high-precision twin-bladed saw into 2-mm-thick laths to reveal their radial surface (Haygreen and Bowyer 1996). The laths were placed in an acetone Soxhlet apparatus for 5 h (Jensen 2007) to remove resins that would cause overestimation of wood density measurements (Schweingruber et al. 1978; Grabner et al. 2005). Samples were air-dried after resin extraction and were then scanned

using the University of Victoria ITRAX scanning densitometer. The digital densitometric images generated were subsequently measured using Windendro® ITRAX software (Version 2008b).

The 12-mm cores were mounted and cut with the twin-bladed saw, as described above, for SilviScan analysis. Sectioned and extracted 12 mm × 2 mm samples were sent to Dr. R. Evans at the Australian Commonwealth Scientific and Research Organization (CSIRO) for analysis. In some cases, where cores were severely broken or contained pockets of rot, the samples were deemed unfit for use with the densitometer and SilviScan systems. These samples included severely broken cores that were difficult to lath to the desired 2 mm width, as well as cores containing rot that would erroneously skew the density and microfibril measurements. Cores that were acceptable for use with SilviScan were trimmed to 7 mm at CSIRO and scanned using the SilviScan densitometer and diffractometry functions. Measurements of maximum density (MXD), mean density (MD), minimum density (MND), microfibril angle (MFA), as well as cell radial and tangential diameters were generated (Lundgren 2004; Vahey et al. 2007). Cell-wall thickness (CWT) was calculated using Eq. (1):

**Fig. 1** Sampling sites in northern British Columbia (triangles) and nearest climate stations to sampling sites (circles). Sampling site ID is as follows: Lower Logging Road (NSx1) and Upper Ski Hill Road (NSx2), Blunt Forest Service Road (NSx3), Gullwing Forest Service Road (NDf4), Jake Forest Service Road (NDf5), Valemount-Jackman's Flats (NDf6)



$$\text{CWT} = P/8 - \frac{1}{2}(P/16 - C/d)1/2 \quad (1)$$

where

$$P = 2(R + T) \quad (2)$$

and  $d$  density,  $C$  fibre coarseness, and  $R$  and  $T$  are the radial and tangential tracheid diameters, respectively (Jones et al. 2005).

### Analysis

Annually resolved site- and species-specific master chronologies were developed from ring width (RW) MXD, MD, MND, maximum cell-wall thickness (XCWT), and minimum microfibril angle (NMFA) measurements (Table 1). RW chronologies were constructed for the six sample sites (Table 1). MXD, MD, and MND chronologies were developed for spruce trees sampled at NSx1 and NSx2, and from fir samples collected at NDf4. Due to their proximity, samples from NSx1 to NSx2 were combined to form more robust maximum cell-wall thickness (XCWT) and minimum microfibril angle (NMFA) chronologies. XCWT and NMFA chronologies were also developed for the NDf4 site.

COFECHA was used (Holmes 1983) to verify the series cross-dating and the resulting time series were transformed into master chronologies using ARSTAN (Cook and Holmes 1986). First, a negative exponential curve was applied to each series (Fritts 1976) and a smoothing spline was subsequently applied only to ring width chronologies, with a frequency–response cutoff of 67 % (Cook and Kairiukstis 1990). ARSTAN's residual chronologies were used for this analysis to minimise autocorrelation. The application of a smoothing spine for standardisation was found to be unnecessary when working with density and fibre data because growth trends due to factors such as inter-tree competition were much less pronounced (Conkey 1986).

Standardised master chronologies were compared to meteorological data from the nearest climate station using response function analysis in PRECON (Fritts et al. 1971; Fritts, 1999) and correlation analysis in SPSS (Version 17). Climate–tree growth relationships identified in PRECON were verified using a simple Pearson's correlation. Cross-correlation tests were performed to determine if lag time was a factor influencing relationships between wood properties and climate variables.

Final reconstructions were developed through linear regressions. The Durbin–Watson statistic was used to

ensure that the observed correlations were not caused by autocorrelation. The independence of variables within each multivariate model was tested using partial correlation, which allows for correlation between two variables to be tested while other variables are held constant. Expressed population signal (EPS) values were used in this study to determine how well the chronologies sample represented the population. EPS is a statistic that reflects the sample size and the  $r^2$  value of a reconstruction (Wigley et al. 1984). Models were restricted in length to EPS values of  $\geq 0.85$ , with only one decade over the chronology length permitted to drop to  $\geq 0.80$  (Wigley et al. 1984). Final predictive models were verified for accuracy using split-period verification, using the most recent 50 % of the observed record as the calibration period.

**Results**

Master chronologies extended into the 17th century, with only a few trees exceeding 400 years in age. EPS values limited the majority of ring width master chronologies to mid-18th century or early 19th century, and most of the density and fibre chronologies to mid-19th century for reconstruction purposes (Table 1).

NSx1 MD and MND, Ndf4 MND, NSx1 and NSx2, and Ndf4 NMFA chronologies were not used for further analysis due to unacceptable EPS values throughout the records. Larger numbers of cores were measured for density and fibre properties from the NSx1, NSx2, and Ndf4 sites, resulting in more accurately cross-dated and statistically representative chronologies. Sample size was smaller than desired for some chronologies due to the loss of viable core samples (rot or breakage) and, therefore, not all of the chronologies created had a statistically reliable EPS value. As only a single core from each tree was measured using the SilviScan system, the MFA and CWT chronologies did

not always cross-date. The Ndf4 MD, MXD, XCWT, and NMFA chronologies are shorter than the existing observed records from the local climate stations (96, 96, 96, and 66 years long, respectively) and are, therefore, only valuable to this study as an example of the type of information that can be derived from different to additional variables in climate reconstruction (Table 1).

The NSx2 and Ndf5 RW chronologies, along with the NSx1 and NSx2 MXD, the NSx2 MND, and the Ndf4 XCWT chronologies were used for further analysis. These chronologies displayed the most reliability (EPS values  $>0.80$  for a significant duration) and minimal autocorrelation according to the Durbin–Watson statistic (ranging from 1.5 to 2.2, with of value of 2.0 representing no autocorrelation) (Table 2). These chronologies also displayed significant correlations ( $\alpha = 0.05$ ) with the annual climate data investigated and, thus, highlight the benefits of multi-proxy reconstructions and multivariate modelling (Table 2).

Figures 2 and 3 show an expanded 6-year section of each climate reconstruction, and are meant to demonstrate that two data points of temperature and precipitation were reconstructed and plotted for each year, rather than one overall annual mean. Figures 4 and 5 show both reconstructions incorporated into one line for the entire reconstruction period. For the Smithers temperature reconstructions in Fig. 4, two points are displayed for each year—June temperature is plotted followed by average July–August temperature. For the Fort St. James precipitation reconstructions in Fig. 5, two points are also plotted—average May–June precipitation followed by average July–August precipitation for each year.

**Temperature**

The RW chronology from NSx2 correlated significantly with the mean June temperature from Smithers ( $r = 0.524$ ,

**Table 2** Statistics describing temperature reconstructions for Smithers area, and precipitation reconstructions for Fort St. James

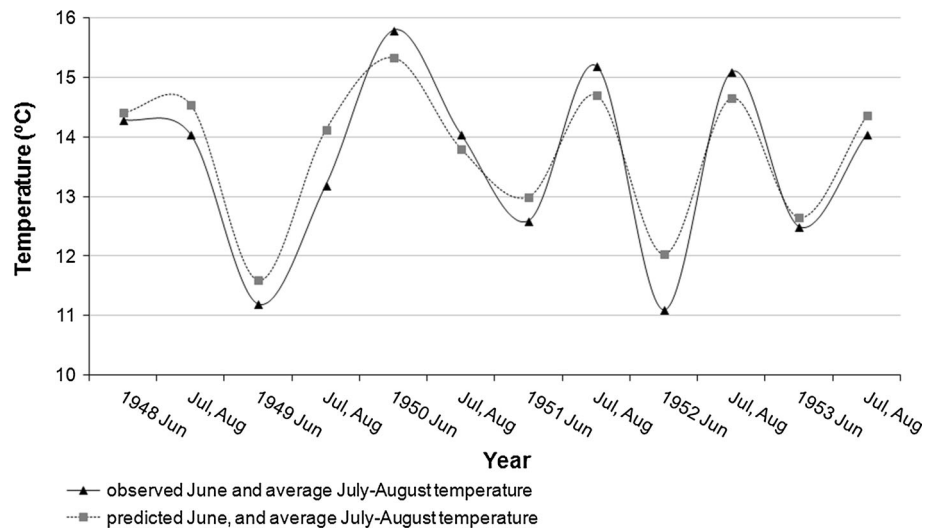
Reconstruction	Mean June temperature (°C)	Mean July–August temperature (°C)	Mean May–June precipitation (mm)	Mean July–August precipitation (mm)
Chronology collection site	NSx2	NSx1 NSx2	NSx2 Ndf5	Ndf4
Species and proxy	Sx RW	Sx MXD Sx MXD	Sx MND Fd RW	Fd XCWT
Pearson’s <i>R</i>	0.524	0.632	0.569	0.552
$R^2$	0.274	0.399	0.323	0.305
Durbin–Watson	1.952	1.503	2.201	1.850
<i>P</i> value	0.001	0.001	0.001	0.001
RE calibration	0.293	0.357	0.367	0.261
RE verification	0.263	0.443	0.327	0.418

*Sx* hybrid white spruce, *Fd* interior Douglas-fir, *RW* ring width, *MXD* maximum ring density, *MND* minimum ring density, *XCWT* maximum cell-wall thickness

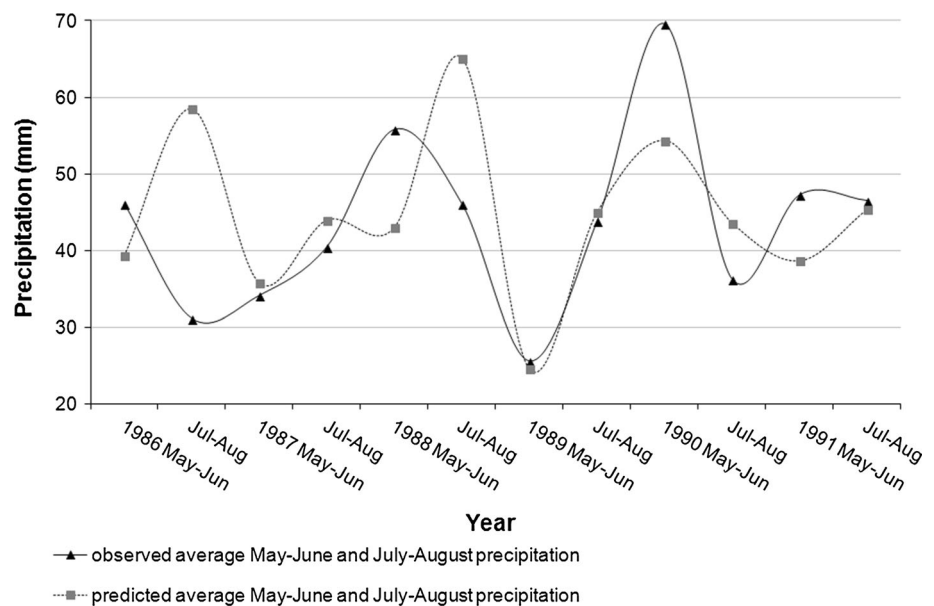
\*  $p < 0.05$



**Fig. 2** A representative 6-year segment of the observed and predicted records of June and average July–August temperature, from 1948 to 1953 for the Smithers area. The model shows two data points per growing season, one for each reconstruction, as opposed to the standard one annual data point



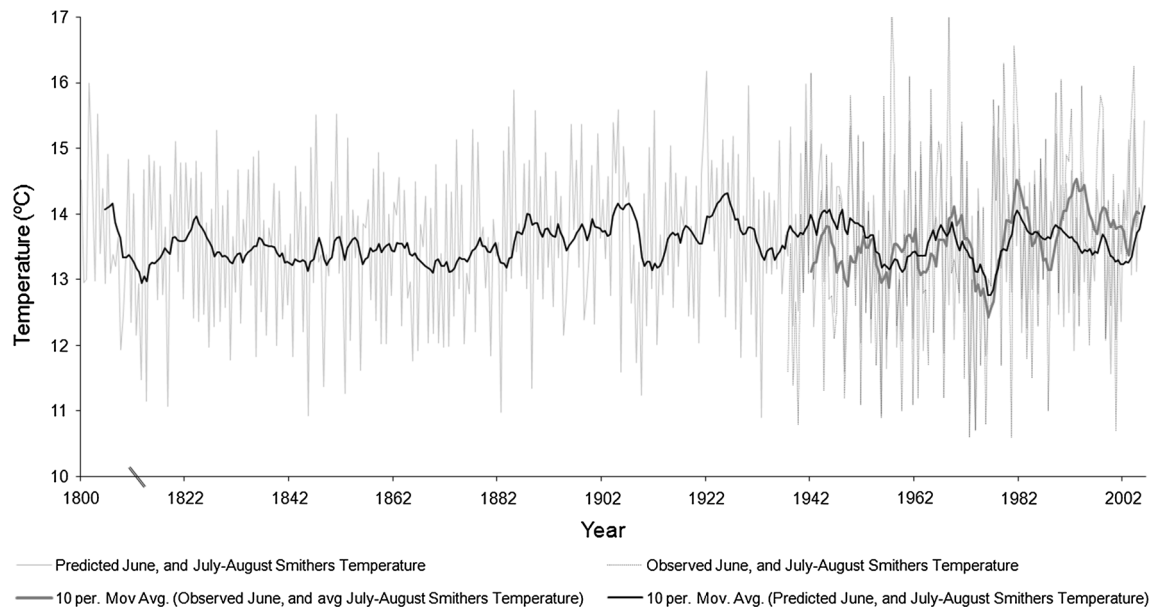
**Fig. 3** A representative 6-year segment of the observed and predicted records of average May–June and July–August precipitation, from 1986 to 1991 for the Fort St. James area. The model shows two data points per growing season, one for each reconstruction, as opposed to the standard one annual data point



$p < 0.001$ ), and was used to reconstruct a proxy temperature record extending to 1805 (Table 2; Fig. 4). The MXD chronologies collected from NSx1 to NSx2 correlated significantly with mean July–August temperature from Smithers ( $r = 0.632$ ,  $p < 0.001$ ), and were used to reconstruct a multivariate temperature proxy record for this area extending to 1791 (Table 2; Fig. 4). The predicted values for each of the proxy records correlate to the original observed datasets, providing verification that the models were accurate. Split verification revealed that the models were significant at 95 % for both verification and calibration time periods according to the reduction of error (RE) statistic (Cook and Kairiukstis 1990) (Table 2).

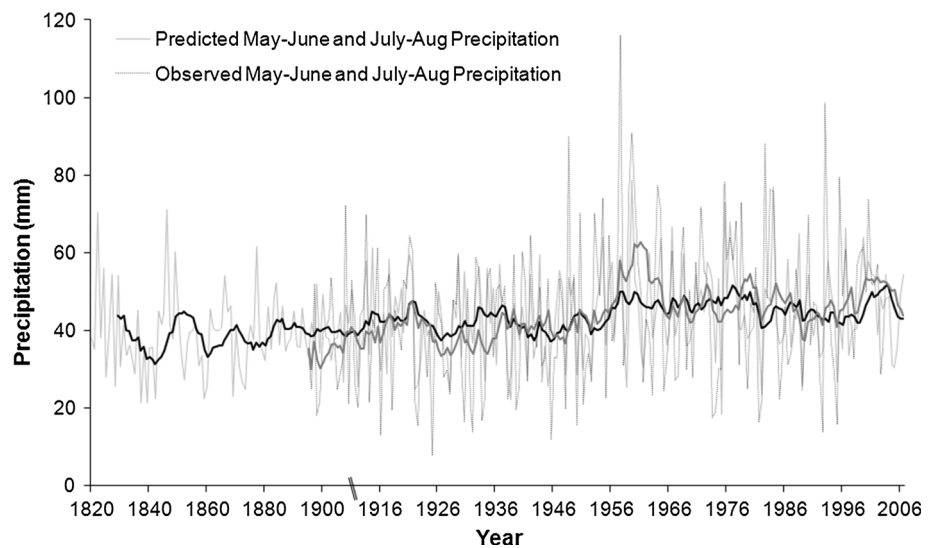
The regression model of mean July–August temperature did not demonstrate multicollinearity when looking at

coefficient collinearity, statistical tolerance or VIF values, but did indicate multicollinearity in the regression eigenvalues and condition index values presented in the collinearity diagnostics in SPSS. Despite the presence of multicollinearity in the model of July–August temperature, the low-frequency trends in the reconstruction remain consistent with the observed data over most of the reconstruction, and therefore it can be assumed that the trends in the predicted data are accurate over time. Figure 4 shows that the reconstructed data follow the measured values accurately. This correspondence is especially important during periods of extreme change such as during the late 1970s and early 1980s, when the measured and reconstructed records show a dramatic increase in temperature. The early half of the 1990s shows a decoupling between



**Fig. 4** The reconstructed model of June, and average July–August mean temperatures for Smithers (to EPS cutoff of 1791). The *black line* represents a 10-year running mean for predicted values; *solid grey line* represents the 10-year running mean for the observed values. Note scale on *x-axis* changes after 1822

**Fig. 5** The reconstructed model of Fort St. James average May–June, and average July–August total precipitation. The *black line* represents a 10-year running mean for the predicted values; *solid grey line* represents the 10-year running mean for the observed values. Model predictions prior to 1915 include only those for the May–June reconstruction; note scale on *x-axis* changes at this point



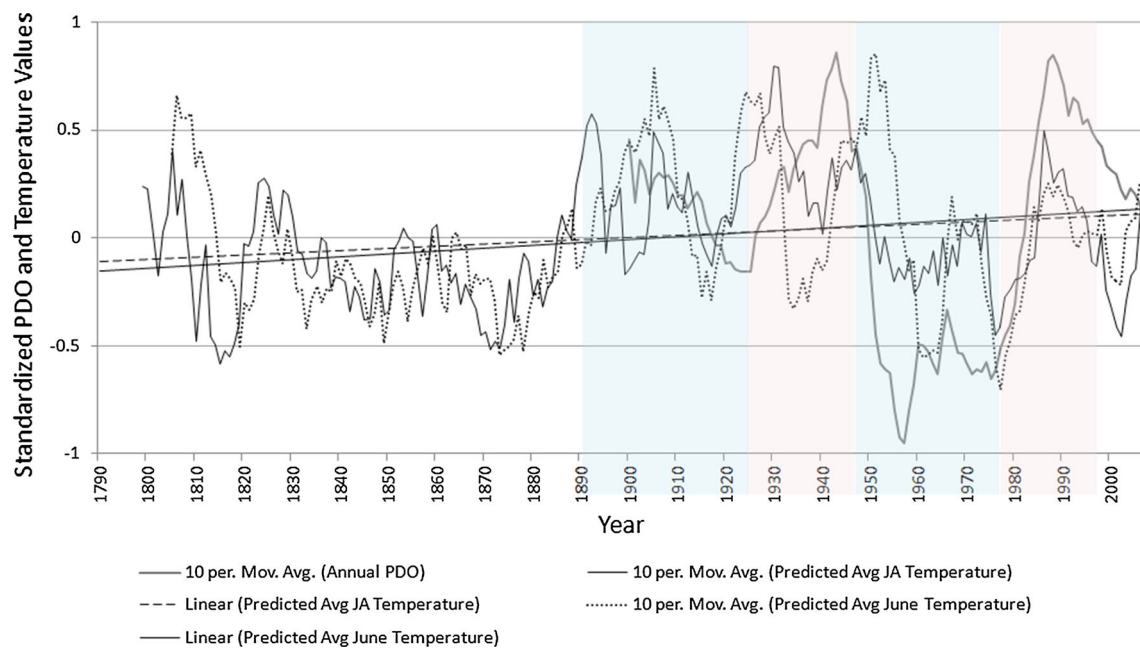
the observed and reconstructed data that is resolved by the beginning of the 21st century. During this brief time period, the model underestimated the observed values.

Periods of cooler-than-average summer temperature are noted in the reconstructions: 1810–1820, 1860–1885, 1905–1915, 1930–1940, 1955–1965, 1975–1980, and 1995–2000. Periods of warmer-than-average temperatures are noted in the reconstructions: 1791–1810, 1885–1905, 1920–1930, 1940–1950, 1980–1995, and 2000–2006 (Fig. 4). Predicted and observed average temperatures over the time series were 13.6 °C, with periodicity in the reconstruction corresponding to annual Pacific Decadal

Oscillation Index values (PDO). Although not strongly correlated for the entire time series, low-frequency similarities between the PDO and the reconstructions of June and July–August temperature were observed (Fig. 6).

#### Precipitation

The Ndf5 RW and NSx2 MND chronologies were used to reconstruct mean monthly May–June precipitation totals for Fort St. James (Table 2; Fig. 5). The resulting proxy record dates back to 1820 with EPS values greater than 0.85. Multicollinearity was shown in the eigenvalues and



**Fig. 6** The correspondence between the average annual Pacific Decadal oscillation (PDO) index values and the average predicted June and average predicted July–August temperatures from this study. Data

have been standardised for comparison and both 10-year running means and *trend lines* are shown. *Blue areas* represent cool periods of the PDO, and *pink areas* represent warm periods of the PDO (colour figure online)

condition index statistics for this model. Multicollinearity inflated the standard errors of the predicted values leading to inaccuracy in the individual predicted years; however, the low-frequency trends are preserved and follow the trends shown in the observed data set (Fig. 5). The only period when the reconstruction does not follow observed trends in the 10-year running mean is from 1955 to 1965, during which the model underestimates the measured data.

The Ndf4 XCWT chronology was used to reconstruct a proxy record of average monthly July–August precipitation for Fort St. James (Table 2; Fig. 5). The resulting proxy record dates back to 1912, with EPS values greater than 0.85.

The predicted values for each of the proxy records correlate to the validation segment of the original observed datasets. Split verification revealed that the models were significant at 95 % for both verification and calibration time periods using the RE statistic (Table 2). Periods of greater-than-average precipitation occur in the reconstructions: 1845–1855, 1905–1920, 1930–1935, 1950–1975 and 2000–2006, with drier-than-average periods characterising the intervals: 1830–1845, 1920–1930, 1940–1950 and 1980–2000 (Fig. 5). Predicted and observed average precipitation levels over the time series were 42.7 and 44 mm, respectively.

## Discussion

There are a number of advantages for exploring a variety of wood properties for use as proxies in dendroclimatology.

Climate affects each wood property in much the same way that ring width is affected; the better (or more optimal) the growing conditions, the more wood that develops (Savva et al. 2010). However, the benefit of using wood properties in dendroclimatology reconstructions lies in the fact that measuring wood over a finer scale lends insight into climate variations within portions of the growing season (Figs. 2, 3), instead of simply deriving an averaged perspective of growing conditions over the entire growing season from the total annual ring width increment as has been the case in most previous studies (Meko and Baisan 2001; Watson and Luckman 2002; Chen et al. 2010; Kern et al. 2013). Intra-annual records have been previously developed using earlywood and latewood widths (Meko and Baisan 2001; Watson and Luckman 2002), however, no sequential climate predictors have been distinguished using earlywood and latewood width proxies. Using the RW and MND proxies for reconstruction of the early portion of the growing season, and then MXD and XCWT proxies for the latter half of the growing season in this study provides a reconstruction of separate, sequential climate periods of the growing season.

Creating a model based on more than one proxy serves to strengthen the output. Multivariate reconstructions of climate often have stronger regression statistics (greater values) (Conkey 1986) and show better correlations to the original climate data. This study supports this concept: when May–June precipitation was reconstructed for the Fort St. James area using RW and MND, the reconstruction



showed an  $r^2$  value of 0.323, indicating that 32 % of precipitation variation in the region can be explained by the variation in the RW and MND combined. However, when May–June precipitation is reconstructed using RW alone, the  $r^2$  value is only 0.202, which has significantly lower explanatory power.

### Reconstructions

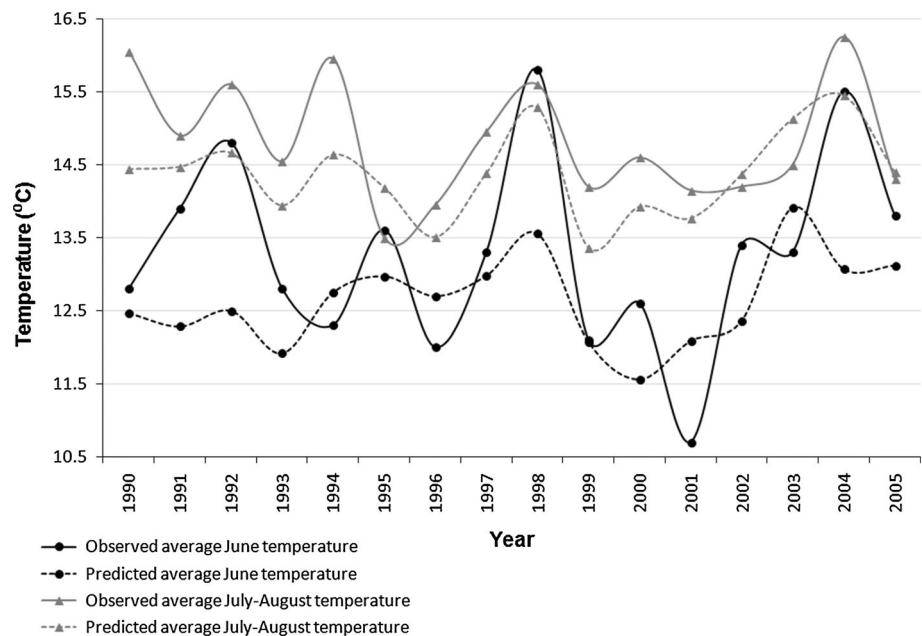
The temperature reconstructions developed in this study show oscillations that are similar to those presented in other dendroclimatic studies in western Canada. Cool periods in the early and late 1800s are present in most previous reconstructions (Briffa et al. 1992; Davi et al. 2003; Larocque and Smith 2005; Youngblut and Luckman 2008), as are warmer-than-average conditions during the mid-1900s (Briffa et al. 1992; Youngblut and Luckman 2008; Flower and Smith 2011). Similarly, our study also shows a cooling trend during the early 1800s and a warming trend in the mid-1900s (Fig. 4). Whilst the temperature reconstructions do not exhibit significant warming over the last century, low-frequency similarities between the PDO and the temperature reconstructions in this study were noted (Fig. 6). These similarities may indicate a growth response of trees at sites NSx1 and NSx2 to PDO-influenced warming and cooling trends.

The reconstruction of average June, and July–August temperature underestimates the observed values from the Smithers climate station during the early 1990s. Although some studies have found that dendroclimatic modelling is problematic in recent decades due to climatic warming trends that create model divergence from observed

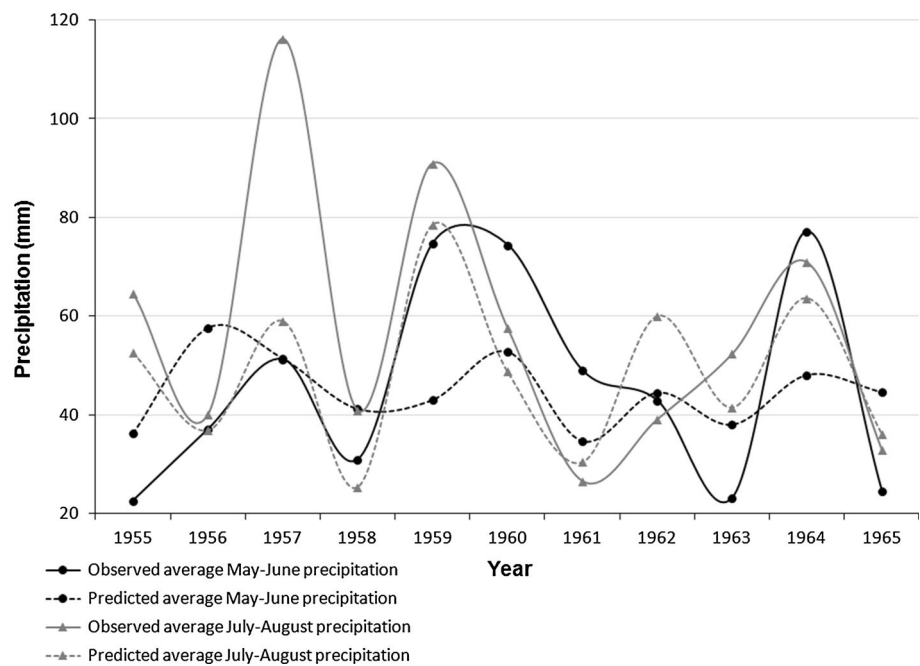
values (D'Arrigo et al. 2008), that is not the case in this study. The temperature reconstruction only underestimates the observed values for a short duration, and then recaptures the observed values accurately from 1999 through to 2006. Had divergence due to climatic warming and a related shift in limiting factor for tree growth been a factor in this reconstruction, we would have expected to see continued divergence over time as the annual regional temperatures continued to increase (D'Arrigo et al. 2008). Figure 7 illustrates that the tree-ring model replicates the decadal variation for both the average June temperature and the average July–August temperature reconstructions. The high recorded June temperature values in 1992 and 1998, and the high average July–August temperature values recorded in 1990 and 1994 combine to skew the 10-year running mean shown in Fig. 4.

The precipitation reconstruction developed in this study shows decadal variation similar to that described by Watson and Luckman (2001). Wetter-than-average periods in the early 1900s and from 1950 through to the 1970s are present in both reconstructions, as well as a drier-than-average period during the 1940s. The similarities between the precipitation reconstruction presented here and that of Watson and Luckman (2001) indicate that the tree growth measured in both studies responded to similar climate forcing mechanisms. From 1955 to 1965, the model underestimates the observed values likely because of the high average precipitation recorded in July–August of 1957, and the high average precipitation recorded in May–June of 1959 and 1960 (Fig. 8). These individual years skew the 10-year moving average shown in Fig. 5.

**Fig. 7** A 16-year segment of the observed and predicted records of average June and July–August temperature, shown on separate lines, from 1990 to 2005 for the Smithers area



**Fig. 8** An 11-year segment of the observed and predicted records of average May–June and July–August precipitation, shown on separate lines, from 1955 to 1965 for the Fort St. James area



### Climate and tree physiology

The temperature models created in this study contain two data points per growing season, as opposed to one data point common to most previous studies. The additional data provided the opportunity to investigate variables that significantly corresponded to early growing season climates and those that corresponded with late growing season climate. Previous studies have been conducted which identified intra-annual variation in climate using earlywood and latewood widths as well as densities (Chen et al. 2010; Watson and Luckman 2002; Meko and Baisan 2001). The advantage that the use of density parameters provides over earlywood and latewood width variables alone is the addition of climate response to late growing season temperatures. The energy that a tree receives is generally allocated to either growth rate or fibre deposition, therefore, there is often a “trade-off” that occurs between these processes (Bouriaud 2005). These individual processes are impacted by climate differently and, therefore, primary relationships between density and ring width and climate can be quite unique. The intra-annual detail provided by density and cell-wall thickness measurements provides an opportunity to reconstruct mean spring and mean summer temperatures and precipitation levels as separate variables. In this study, we were able to reconstruct the chronological May–June and July–August temperature variables because we used ring width parameters in combination with density parameters to capture the best relationships with temperature or precipitation during those specific growing season intervals. Ring width and minimum density most

accurately captured early growing season temperature and precipitation, whilst maximum density and maximum cell-wall thickness most accurately captured late growing season temperature and precipitation for the given areas studied. The reconstruction of late growing season temperatures is not always possible with growth rate variables alone; density variables can be used to fill this gap (Wood and Smith 2013; Xu et al. 2012a; Chen et al. 2010). These wood and fibre measurements also provide a greater pool of data to test for growth response to climate. Identifying seasonal growth response could reveal spring and summer climate differentiation unavailable from annual ring width data alone. This intra-annual insight is useful for distinguishing years where growth initiation is delayed due to the summer droughts and early frosts that are characteristics of both northern climates and changing climates. In the following paragraphs, we discuss possible tree physiological responses to the climate regimes in the northern areas studied.

In the Smithers area, RW shows the strongest response to June temperature. This finding indicates that trees in this area are completing the majority of their radial growth during the early summer; the time of the season when the earlywood is being formed, cells are dividing and expanding in size (Kozłowski 1979). Incremental ring width growth continued into July (Green 2007) and, therefore, a reconstruction of solely June temperature, as opposed to an average of June and July temperatures, using ring width may be unusual. However, the strong correlation between June temperature and ring width can be attributed to the dependency of tree growth initiation on the date of

spring snow melt. Pitman and Smith (2013) demonstrated a significant negative relationship between spring snowpack and ring width in mountain hemlock (*Tsuga mertensiana*); cooler spring temperatures and higher snowpacks, at high-elevation sites, resulted in a narrower ring.

Maximum ring density chronologies for both the NSx1 and NSx2 sites were strongly correlated to mean July–August temperatures. Latewood in these tree rings forms in the latter half of the summer months when growing season cues, such as photoperiod, trigger cell-wall thickening (Savva et al. 2010). Sustained warm temperatures later in the summer have a positive effect on the latewood density, with more cellulose and lignin deposited in the cell walls, increasing the density of the wood (Kozłowski 1979; Conkey 1986). Denser cell walls are indicative of hotter July/August temperatures and/or a longer growing season.

At the NDf5 site, annual ring width was positively correlated to May and June precipitation. Larger earlywood cells form with more precipitation (Conkey 1986), thereby increasing the width of the annual ring.

The annual minimum density measured at the NSx2 site was positively correlated to May and June precipitation. Thus, with greater spring precipitation amounts, the lower range of density values, which are usually found in the earlywood, are higher than average. This finding is opposite of what was expected—usually greater precipitation leads to larger, and less dense earlywood cells. This physiological outcome indicates that the cell enlargement was hindered by the presence of increased precipitation; denser wood in the spring-enlargement phase of growth suggests that the cells were unable to grow to a large size. High-elevation sites (>1500 m a.s.l.), such as NSx2, experience delayed snow melt, spring freeze–thaw events, and large amounts of spring run-off (Rodríguez-González et al. 2010). In these situations, soils often become saturated and precipitation can hinder cellular growth due to a reduction in nutrient availability and gas exchange capability (Rodríguez-González et al. 2010). The tracheids produced under such conditions will have a lower lumen to cell size ratio, which equates to wood with a higher minimum density.

Maximum cell-wall thickness was negatively correlated to the mean July–August precipitation levels at the NDf4 site. This finding indicates that as the precipitation levels increased, the cells produced on average were lower in density. During July and August, wood formed in the annual ring has completed its cell enlargement phase and has moved into cell-wall thickening (Kozłowski 1979). A negative relationship between cell-wall thickness and precipitation indicates that increased precipitation was preventing optimal cell-wall thickening from taking place. This relationship may be a consequence of cloud cover. Higher levels of precipitation are accompanied by

increased cloud cover, which decreases the energy available to the tree for the deposition of cellulose and lignin fibres to the cell wall, therefore, decreasing the maximum density (Polge 1970).

#### Wood and fibre proxy data

It was assumed that all of the wood property characteristics examined, as well as the chronologies developed from these properties, would be climate sensitive (Hillar 1964; Evans et al. 2000). Whilst we show that density and cell-wall thickness were highly climate sensitive, a number of other wood property–climate relationships did not allow for robust reconstruction. Fibre properties such as MFA are not commonly used in climate reconstruction due to the cost of the analysis, however, there is evidence suggesting that MFA is responsive to water stress, and, therefore, may share a negative relationship with precipitation (Xu 2012b; Donaldson 2008; Wimmer et al. 2002). Moreover, MFA has demonstrated relationships to temperature and length of growing season (Xu 2012b; Youming et al. 1998; In Donaldson 2008). It is possible that formation of microfibril angles, and cell radial and tangential diameters were not only conditioned by climate, but were also influenced by genetic variables which modified their relationship to climate at our study sites. It is also possible that the fine-scale variability detected in the microfibril angle was not influenced by the monthly or annual climate variables considered in our analyses. In addition, the microfibril and cell diameter chronologies that were unacceptable for use in our analyses due to low EPS values could reflect the sample sizes employed.

The NDf4 chronology is limited in duration and did not allow for reconstruction of climate variables preceding the Fort St. James instrumental record. Nonetheless, the chronology did provide an opportunity to consider whether parameters such as maximum cell-wall thickness provide robust relationships sufficient for climate reconstruction. We were able to show that changes in cell-wall thickness do record late summer month variations in climate, allowing for greater detail in climate reconstruction than what is feasible with annual ring width alone. For example, the reconstruction of June and July–August temperatures (Fig. 8) shows that during the early 1950s June temperature was actually higher than the mean July–August temperature for the Smithers region. Although the climate of this interval is contained within the instrumental record, the detail provided by our evaluation of cell-wall thickness illustrates the potential insights that can be derived from extended reconstructions that employ multiple proxies. Identifying signature years such as this warm period in the early 1950s could potentially act as an explanation for phenomena such as extreme forest fire conditions or

extended drought, and therefore be important to forest managers for planning prescribed burning schedules and budgeting for fire season resources, and to local communities for planning water use. Acquiring insights such as these are certain to become increasingly important, as changes in the climate of northern British Columbia progressively impact local areas and species.

## Conclusion

This study investigated historical climate trends in northern British Columbia through the use of tree-ring proxies, and established a means of reconstructing intra-annual climate patterns from wood density, fibre properties, and tree-ring width data. Specific attention was given for investigating how dendroclimatological analyses of intra-ring wood and fibre properties can be interpreted to improve proxy climate records.

A mean June temperature proxy record dating to 1805 and a July–August mean temperature proxy record for Smithers extending from 1791 to 2006 were constructed from spruce ring width and maximum density chronologies. Douglas-fir ring width, spruce minimum density, and Douglas-fir maximum cell-wall thickness chronologies were used to reconstruct a May–June precipitation record extending from 1820 to 2006, and a July–August total precipitation record for Fort St. James that extends from 1912 to 2006.

The results presented in this study demonstrate that a combination of multivariate and single-variate analyses provides detailed insights into seasonal radial growth characteristics. These findings allowed for the reconstruction of intra-seasonal climate variables that reflected physiological responses to climate at different times throughout the growing season. Intra-seasonal historical climate information provides insight into climate phenomena such as extreme drought years and shorter-than-average growing seasons by elucidating temperature and precipitation fluctuations throughout the growing season. Although trees in this region are relatively young due to natural and anthropogenic disturbance regimes, detailed historical climate records are available through the use of multiple wood proxies.

**Author contribution statement** Lisa J. Wood: responsible for data collection and analysis. Provided initial manuscript draft and involved in editing different versions. Dan J. Smith: supervised the research and provided support funding. Reviewed and edited different versions of the manuscript.

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