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Quercus macrocarpa annual, early- and latewood widths as hydroclimatic proxies, southeastern Saskatchewan, Canada

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Abstract. Fluctuations in size of annual ring-widths of *Quercus* species suggest that environmental factors influence the size and density of vessels within the ring, either by acting as a limiting factor for growth or through fine tuning of the wood structure to environmental factors. The purpose of this study is to assess the potential of *Q. macrocarpa* to provide multiple dendroclimatic proxies for the Canadian Prairies, by investigating growth responses of annual, early- and latewood widths to regional climate variability. Results indicate that ring width chronologies, from southeastern Saskatchewan capture regional signals related to moisture and drought conditions. Correlations suggest that late-wood widths are more representative of annual ring-widths, than are early-wood widths, and are the best proxy of seasonal fluctuations in climate. Thus regression models that include latewood widths were able to account for more variance in the Palmer Drought Severity Index (PDSI) than when annual ring-widths are used as the only proxy. This study demonstrates that *Q. macrocarpa* can provide multiple dendroclimatic proxies for investigating large scale climatic fluctuations at annual and sub-annual time scales. It is novel in terms of sub-annual analysis of tree-rings in a region that previously lacked dendrochronological research.

1. Introduction

The Canadian Prairie region accounts for 82% of the cultivated land in Canada and is an important supplier of food for the global community, with agricultural commodities ranging from various grains, through legumes and oilseed, to both grain and grass-fed meat products [1, 2]. The predicted global warming of 1.4 to 5.8°C between 1900 and 2100 [3], demands understanding the vulnerability of the Prairie region to climate change and developing adaptation strategies [4]. Studying past climatic change puts current trends in perspective, reveals the mechanisms that govern the Earth's systems, and provides data to test predictive models and to evaluate the impact of climatic change on biological and geographical systems and processes [5]. Absolutely dated tree-ring chronologies are an important archive for evaluating both past and current natural climate variability occurring over centuries and millennia, as well as changes over recent decades and annual time frames [6]. As well, tree-rings offer the greatest potential for studying climatic and environmental variability at local and regional levels, because of the wide geographical distribution of suitable sites, high temporal resolution (annual or even seasonal), high replication factor and environmentally sensitive (*i.e.* accurate) nature of their growth patterns [7]. Most ring-width records for the Prairies are derived from trees growing along the margins of the Prairie Ecozone, [8] mostly because long-lived species are rare in the subhumid northern Great Plains [9]. Notable exceptions of long- tree-ring chronologies have been obtained from

Quercus species found scattered throughout the Prairies and Great Plains region [8, 10, 11, 12, 13]. Investigations of *Q. macrocarpa* (bur oak) in Nebraska and the Dakotas have indicated the longevity (most commonly 200 to 300 years old, with some samples reaching ages of over 700 years old) and moisture sensitivity of this species and its potential for drought investigation [8, 13].

Comparisons between patterns of annual layers of *Quercus* tree-rings and climate records suggest that these parameters may serve as potential climate proxies, whereby climatic factors influence the size and density of vessels within the ring, either by acting as a limiting factor for growth or through fine tuning of the wood structure to environmental (water) conditions [8, 13, 14]. Vessels are an advanced evolutionary trait of angiosperms that enable the trees to more efficiently transport water up the tree. Under normal growing conditions, ring-porous trees develop single or multiple rows of large conductive vessels in the spring (earlywood) and form smaller vessels (latewood) during the rest of the growing season [15]. In general, *Quercus* species have the ability to sustain stomatal conductance at low soil and leaf water potentials and have an inherently low capacity for water loss that contributes to their success in dry locations [16]. When water availability is limited during the growing season, disruptions in the physiological process that control cambial growth most often causes anomalous tissue development within the annual ring [17]. Diameter and density of the vessels have been related to vulnerability to water stress [18], with smaller, denser vessels, and narrower annual rings, predominantly being associated with an abnormal growth year (such as during floods or droughts) [17].

The size and density differences within each annual ring are imparted by differences in rates and durations of cell processes [19], resulting in the formation of early- and latewood. Latewood holds potential for studying summer drought; however, the application of latewood data to paleoclimatology has been limited by relatively few chronologies that have been developed and analyzed [19], and nearly all of these studies have examined the climate sensitivity of earlywood or latewood in coniferous species [19, 20, 21, 22], where ring boundaries are identified by examining the size and cell wall thickness of the tracheids. Therefore, with the highly distinguishable sub-annual differentiation of cellular structure/growth patterns found in ring-porous gymnosperms such as the *Quercus* species, the goal of this study is to assess the potential of *Q. macrocarpa* to provide multiple dendroclimatic proxies for the Canadian Prairies by investigating growth responses of annual, early- and latewood widths (RW, EW, and LW, respectively), to regional climate variability (*i.e.* climate variables such as temperature, precipitation and the Palmer Drought Severity Index, PDSI).

2. Methods

2.1 Tree-ring data

Cores and cross-sectional discs of bur oak trees were sampled from five sites within the Qu'Appelle Valley of southeastern Saskatchewan (Figure 1). As in conventional dendroclimatic studies, all samples were collected and prepared for analysis as described by Stokes and Smiley [23] and Fritts [6]. After surfacing, samples were scanned using an Epson® Expression 10000 flatbed scanner, at resolutions between 800 and 1200 dpi, depending on the clarity of the image required. Higher resolution images were required for enabling the distinction of narrow rings in periods of suppressed growth if the coarser resolution was deemed inefficient for this purpose. Dating, measuring and visual crossdating of annual rings were carried out using the program WinDendro™ Density (version 2008b). Early- and latewood width measurements were aided by the distinct size differentiation of early- and latewood vessels in bur oak samples. Early- and latewood measurements were based on a defined boundary of 40% of the minimum to maximum relative pixel density in the reflectance values, where the onset of latewood growth was noted as having more dense and compacted vessels being darker in nature. Some early- latewood boundaries were adjusted manually to correct for errors in the automatic detection process.

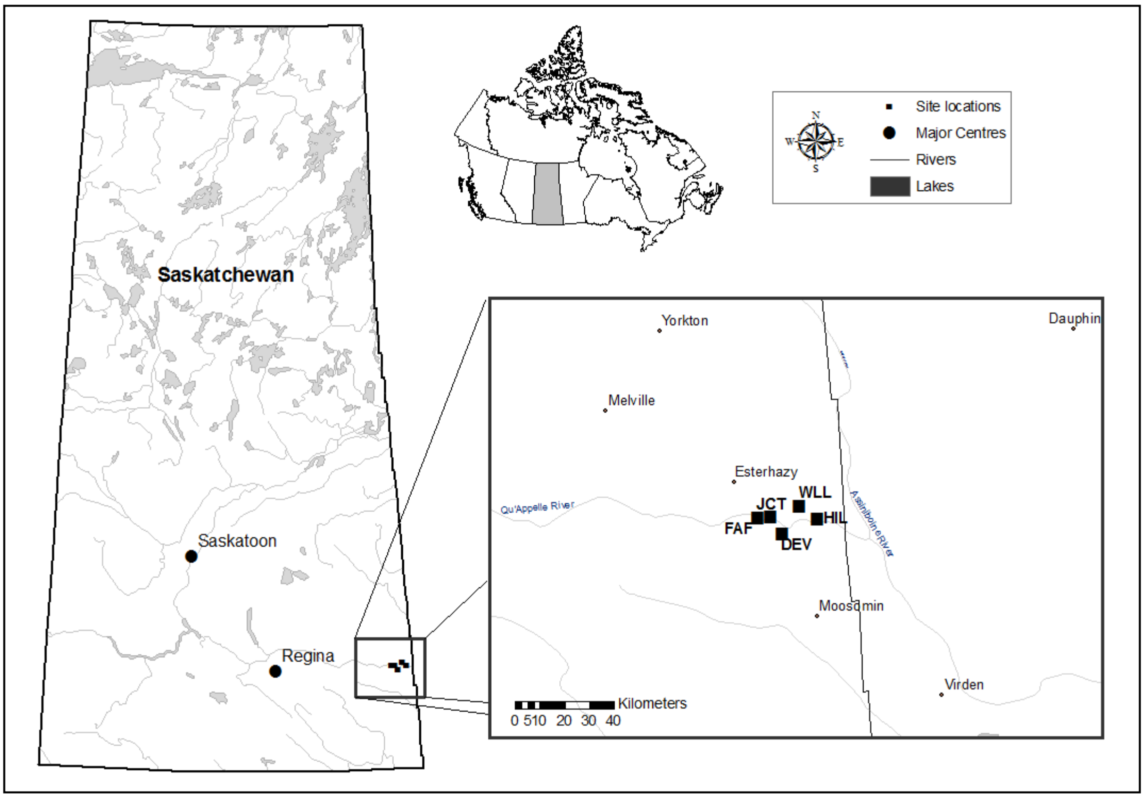

Figure 1. Chronology site locations in southeastern Saskatchewan.

COFECHA was used to verify crossdating and provide chronology statistics that describe the strength of intercorrelation between tree-ring samples at each site (Table 1) [24, 25]. Sites were individually crossdated and then combined to produce three regional chronologies (a single regional chronology each for RW, EW and LW). Tree-ring series were detrended to remove non-climatic variation associated with aging of the tree and ecological events such as suppression and release within the tree-stand. The spline used to detrend the series had a 50% response wavelength equal to 70% of the length of each ring-width series, retaining an approximate upper limit of variance found at 65 year frequencies. Regional standard (detrended index chronology); [6]) and residual ('prewhitened'; autocorrelation is removed using autoregressive modelling) [26]) chronologies were produced and were subsequently used throughout the analyses.

Table 1. Chronology statistics for each site incorporated into the regional chronology.

Site Name	Code	Chronology Type[a]	# Cores	# Trees	Chronology Interval	Mean Length (Yrs)	Mean Sensitivity	Interseries Correlation	Between tree Correlation	Year EPS >0.85	Year SSS >0.85
Devon Farm	DEV	RW	26	14	1854-2005	83.0	0.291	0.582	0.421	1913	1910
		EW					0.239	0.338	0.181	* never	1920
		LW					0.515	0.555	0.402	1917	1910
Faffard's	FAF	RW	33	19	1886-2006	77.2	0.220	0.573	0.386	1918	1916
		EW					0.219	0.344	0.178	1941	1928
		LW					0.407	0.565	0.335	1920	1917
Hill Side	HIL	RW	14	7	1907-2004	85.9	0.306	0.603	0.486	1908	1908
		EW					0.222	0.369	0.19	* never	1910
		LW					0.517	0.595	0.478	1908	1908
Junction	JCT	RW	14	9	1813-2007	131.0	0.239	0.539	0.37	1891	1857
		EW					0.231	0.254	0.103	* never	1891
		LW					0.548	0.342	0.326	1893	1867
Wildlife Lands	WLL	RW	50	27	1831-2006	100.9	0.251	0.674	0.525	1883	1866
		EW					0.219	0.254	0.247	1902	1892
		LW					0.544	0.625	0.505	1883	1866

[a] Chronology Type: RW - annual ringwidth; EW - earlywood; LW - latewood

2.2 Instrumental climate data

Regional climate variables were derived from gridded climate data for the Prairie region (45° to 60° N and 90° to 120° W). Monthly temperature data were extracted from the CRUTEM3+HadSST2 gridded (0.5°) dataset [27] while monthly precipitation were extracted from Mitchell and Jones' [28] CRU TS 3 - New World gridded (0.5°) dataset. These data were reduced to annual and seasonal (DJF, MAM, JJA, SON) means and totals. Gridded Palmer Drought Severity Index (PDSI) records [29] were also extracted for the Prairie region and evaluated on a month to month basis with the regional chronologies. Because of the scarcity of climate stations on the Canadian Prairies prior to the 20th century [8], all data records were evaluated for the 20th century only (1900 - present).

2.3 PDSI reconstructions

Tree-ring indices were examined for correlations with PDSI, and climate data for the grid point location having the highest absolute correlation (51.25°N, -103.75°W, near Estevan, SK, found with each regional chronology), were extracted for reconstruction purposes. For the regional tree-ring indices used as predictors of PDSI, the length of the chronology was limited to the segment where the subsample signal strength (SSS; a measure of the chronology's ability to retain its original signal back through time; [30]) was above 0.85 (Table 1). Linear regression models were developed by a user-written MATLAB function [31] to estimate PDSI from a set of standardized regional tree-ring predictors through a forward step-wise procedure. Forward and negative lags of up to two years allowed the model to accommodate relationships between drought and tree growth response in the growth year and two years following [6]. The model was validated using the leave-*n*-out cross-validation method. Regression residuals were tested for autocorrelation using the Durbin-Watson test [32], and the mean variance inflation factor (VIF) was calculated to detect multicollinearity in the models.

3. Results and discussion

3.1 Regional chronologies

Standardized and residual regional chronologies (RW, EW and LW), show the coherence of ring-width variability over the entire length of the chronologies (1813 - 2007) exhibiting similar patterns of growth over long-term changes (Figure 2). The chronologies display the same pattern of sustained high growth in the mid 1940s to late 1950s, and suppressed growth in the mid 1800s, 1920s and late 1900s. Based on series intercorrelations and between-tree correlations (Table 1), it would appear that EW chronologies may be less sensitive and responsive to climatic fluctuations influencing tree-ring growth. Given that these two statistical parameters (inter- and between-tree correlations) have similar values for both LW and RW chronologies, it further suggests that latewood widths are more closely related to annual ring-width indices in the timing and magnitude of tree-ring growth response to climatic fluctuations. Correlations among the three chronology parameters (RW, EW, and LW; Figure 3) provides further evidence to support this claim, suggesting that LW indices capture similar, coherent signals, most likely related to regional climate, as depicted in RW series; and could therefore be useful as an as of yet underutilized archive of dendroclimatological material.

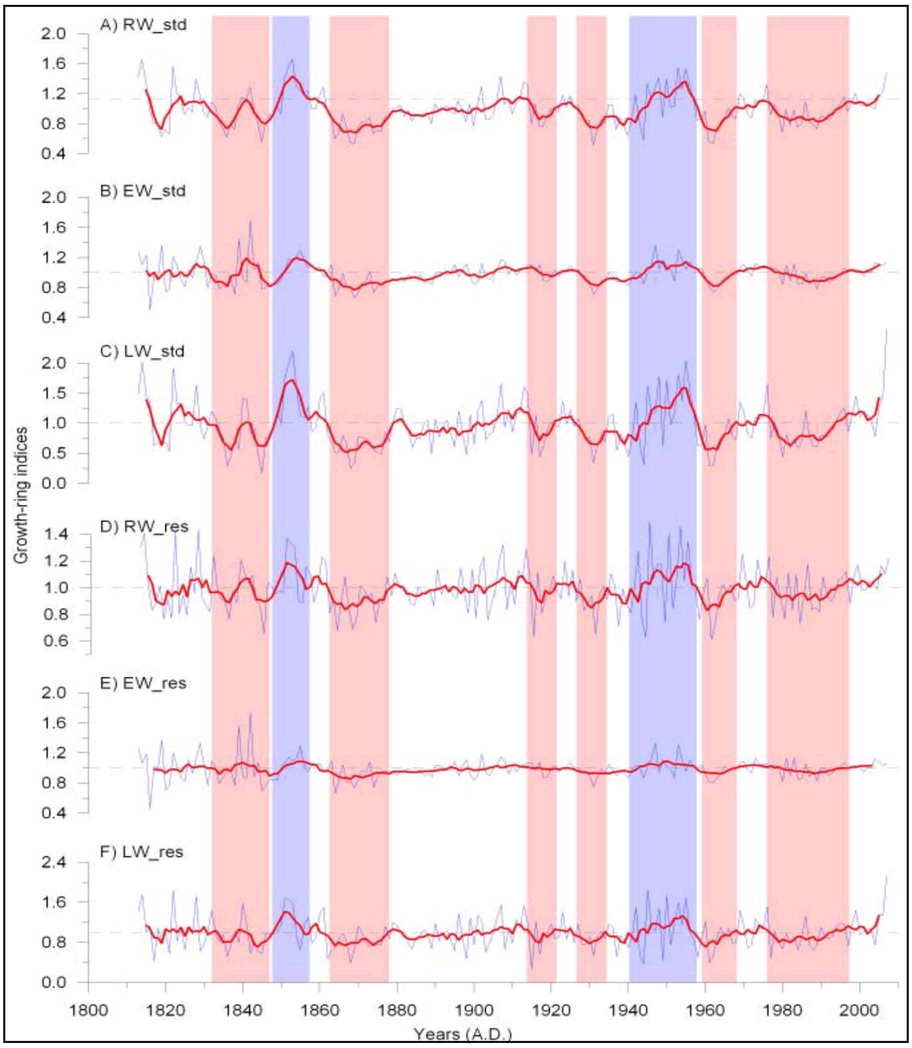

Figure 2. Standardized (std) and residual (res) growth-ring indices for the period 1813-2007. Chronologies are smoothed by a 9 year running average (red). Pink shading indicates years of suppressed growth (below the mean), and blue indicates periods of rapid growth above the mean.

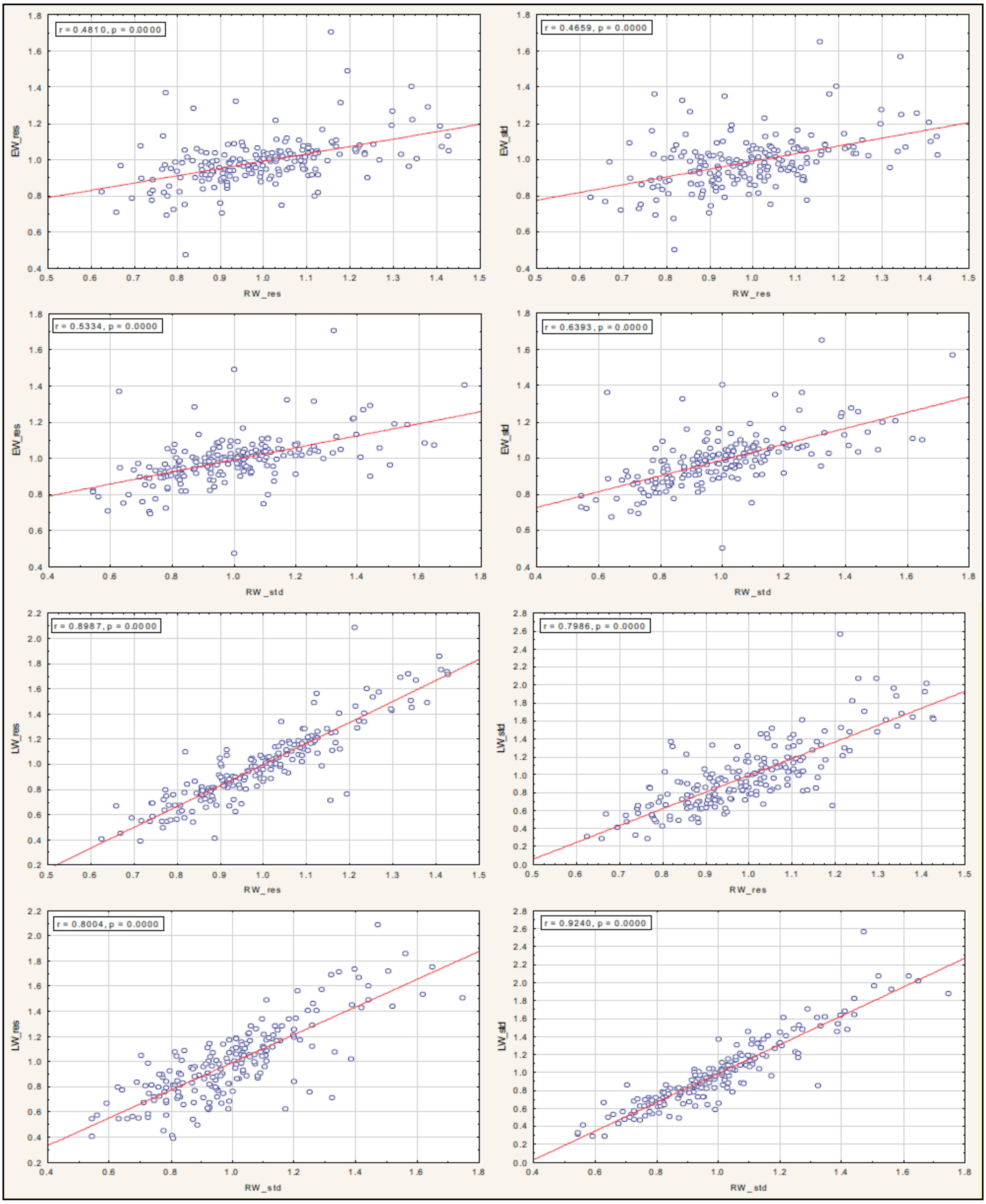

Figure 3: Correlations between annual ringwidth (RW), earlywood (EW) and latewood (LW) chronologies. Correlations are significant at the $p < 0.00001$ level.

3.2 Growth responses to climate

With both standard and residual regional chronologies, RW, EW and LW ring-width indices are positively correlated with precipitation and PDSI values, and negatively correlated with temperature (Figure 4). This is an indication that moisture stress is the major limitation to growth of the species at its western ecological range [8, 13]. Residual indices of each chronology had higher and more widespread correlations with both precipitation and temperature however standardized indices were more strongly correlated with PDSI data values for the Prairie region (Figure 4).

3.2.1 Temperature correlations. In general, RW, EW and LW regional indices have a weak negative correlation with May temperature ($r = -0.3$ to -0.4; $p < 0.05$, results not shown for correlations with standard chronologies; Figure 4) over a relatively wide area, encompassing much of the Prairie region under study. Annual and seasonal temperatures had no significant correlations with either the residual or standardized chronologies (results not shown). The weak negative growth responses suggest that regionally higher spring temperatures impose high evapotranspiration demands, resulting in reduced annual ring growth.

Earlywood chronologies had the most significant and widespread negative correlations to temperature, corresponding to the negative effect of temperatures earlier in the year. During the cold (winter) months, ring porous species such as bur oak enter a quiescence phase in which it gains the ability to respond to growth-promoting conditions. During quiescence, before photosynthates are yet to be produced, the tree uses stored reserves from the previous growing season [33], and only changes at the ultrastructural level occur within a tree (*i.e.* EW vessel formation; [34]). Visible signs of activity appear when the conditions become favourable for LW growth; thus, warming spring temperatures and increasing evapotranspiration demands, correlate negatively with the production of EW growth (Figure 4), potentially deeming it a proxy for spring temperatures.

3.2.2 Precipitation correlations. Annual, EW and LW growth indices are primarily correlated with summer (JJA) precipitation ($r = 0.2 - 0.5$; $p < 0.05$, results not shown for correlations with standard chronologies; Figure 4). Correlation analyses show that regional RW and LW display a similar sensitivity to summer precipitation, while the moisture signal in EW is much weaker, further supporting the closer relation of LW to RW widths than to EW widths. Correlations between spring, autumn, winter (prior autumn and winter) and all ring-width series were not significant at the regional level (results not shown). Although chronologies were found to be significantly correlated with summer precipitation only, residual growth indices also correlate with annual (June to May) precipitation (not shown), "but this correspondence likely reflects the importance of summer rainfall on the Prairies rather than a real physical relationship between ring-width and total annual precipitation" [8]. If an 'actual' significant annual correlation were to exist, growth indices would likely have some correlation with other seasons, most likely with prior winter precipitation, reflecting the importance of winter snowfall to soil moisture recharge and growth resumption in the spring [13, 35].

3.2.3 PDSI correlations and reconstructions. Unlike analysis of temperature and precipitation, standardized RW, EW and LW regional chronologies have stronger positive correlations with monthly PDSI values than do residual chronologies. PDSI data and regional chronology correlations were significant for all months (January through December; results not shown), however the strongest association was found during May ($r = 0.4$-0.6; $p < 0.05$, results shown for correlations with standard chronologies only; Figure 4). Correlation throughout the year results from the autocorrelation with both standardized chronologies and the PDSI. Successive years of moisture limited growth, will result in suppressed growth in the following years. Similarly, PDSI for a given month or season depends partly on previous months' moisture conditions through soil-moisture storage and autoregressive terms in the computation algorithm [36]. Therefore, monthly PDSI values reflect moisture conditions not

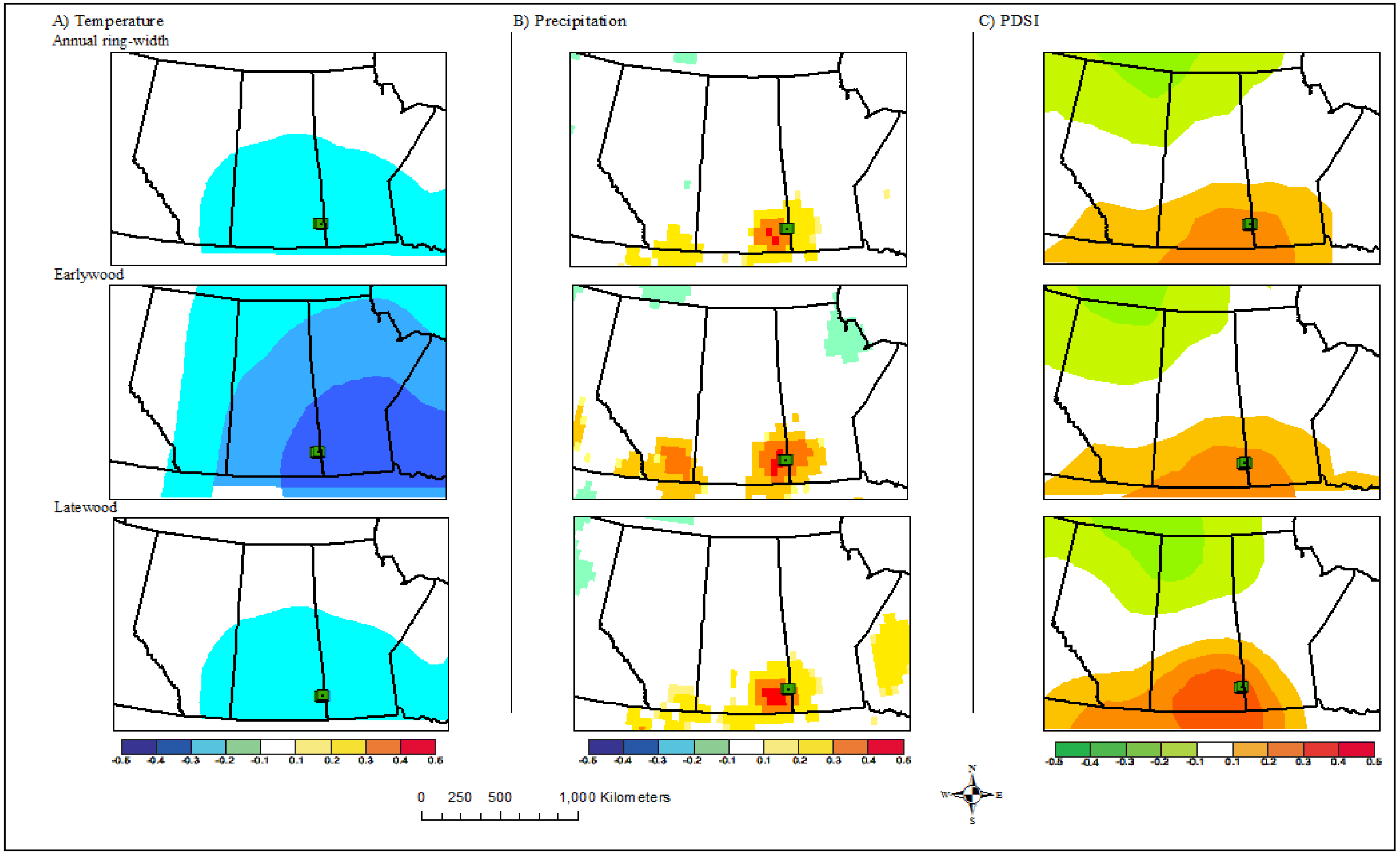

Figure 4. Correlation analysis between A) monthly (May) mean temperature; B) summer (JJA) precipitation; C) monthly (May) PDSI, for the period 1900 - 2003. Correlations shown are significant at α = 0.05. Site locations are denoted by the green squares.

only for that month, but also several months preceding the timeframe in question [19]; which is ultimately reflected by the autocorrelated growth responses of the tree-ring widths.

Latewood chronologies again display more similarities in levels of significance and spatial coverage to the RW indices. Because of the strong correlations between standard chronologies and PDSI data, reconstruction models (Figure 5; Table 2) were generated for RW and LW to assess the applicability of these indices as proxies of PDSI. Regression models were skilful and significant (Table 2) and the Durbin-Watson statistic showed that residuals from both models were uncorrelated [37]. In the verification period, reconstructions were significant and the positive values for the reduction of error (RE) statistic indicate that the models have significant predictive capabilities [6].

Both models accounted well for the timing and magnitude of severe 20th century summer droughts (Figure 5) in the region, and were successful in depicting the peaks and lows of interannual variations in the instrumental data; PDSI values ranging from 0 to -4 (0 being no drought, -4 representing severe droughts). Although both models are able to adequately reconstruct PDSI, the LW model was able to account for more variance than when using the RW indices as predictors of PDSI (35.5% and 32.5%, respectively). The mean variance inflation factor (VIF; Table 2) is below the critical threshold for reconstruction purposes [38], suggesting that multicollinearity is not an issue, and the model is valid. The use of LW widths as proxies allows for sub-annual analysis and a more in depth understanding of seasonal hydroclimatic variability for the Prairie region; an area that frequently is faced with the consequences of drought and heavy reliance on the summer growing season for the sustainability of its agricultural economy.

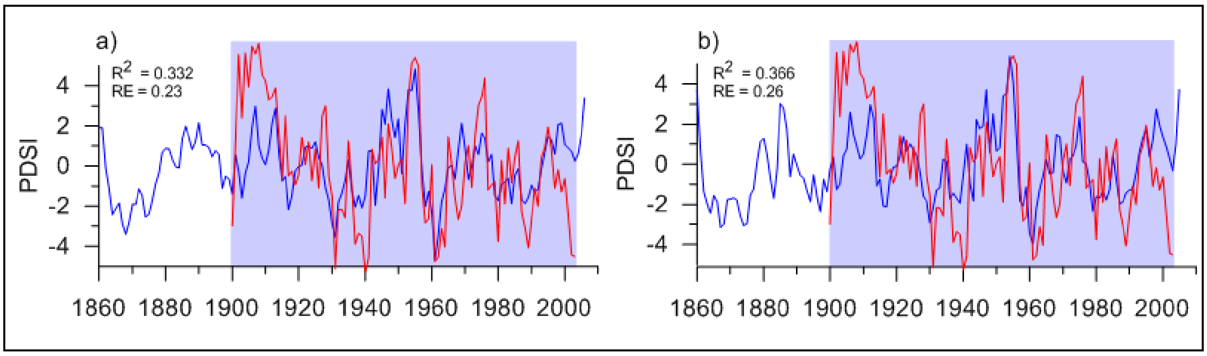

Figure 5. Total annual ringwidth (a) and latewood (b) proxy reconstructions of PDSI near Estevan, SK for the period 1860 to 2005. Red lines are observed instrumental data values, and blue lines are reconstructed values of PDSI. Shading of the blue box indicates the calibration period for the models (1900 - 2003).

Table 2. Regression statistics of PDSI reconstructions.

Name	Period	Length (yrs)	Calibration Period	Lag	Predictors	R^2	R^2_{adj}	RE	SE	DW	VIF_{max}
LW_PDSI	1860-2005	146	1900-2003	±2	2	0.366	0.353	0.26	2.27	H_0	1.18
RW_PDSI	1860-2005	146	1900-2003	±2	2	0.332	0.325	0.23	2.45	H_0	1.18

Proxy	Model
LW	$-6.0600 + 4.5715*LW + 1.7044*LW_{+1}$
RW	$-10.5025 + 6.0773*RW + 4.6406*RW_{+1}$

R^2: multiple correlation coefficient.

R^2_{adj}: Multiple correlation coefficient adjusted for degrees of freedom.

RE: Reduction of Error statistic; any value greater than 0 indicates value in the reconstruction.

SE: Standard deviation of the differences between the actual values of the dependent variables and the predicted values

DW: Durbin-Watson statistic: H_0 - no first order autocorrelation in residuals.

VIF_{max}: Variance inflation factor, used to detect multicollinearity in the models.

4. Conclusions

This study demonstrates that *Q. macrocarpa* can provide multiple dendroclimatic proxies at annual and sub-annual time scales, for investigating large scale climatic fluctuations that influence the climate of the Prairie region. Results indicate that RW, EW and LW chronologies from southeastern Saskatchewan capture signals related to regional moisture and drought conditions. Significant negative correlations to temperature and positive associations with precipitation and PDSI indicate that trees in this region are thus limited by moisture availability and are sensitive to drought. Correlations between RW, EW and LW chronologies suggest that LW widths are more representative of annual ring-widths, and are the best proxy of seasonal fluctuations in climatic data, explaining more variance in PDSI.

Reconstructions indicate that regional LW widths are the most significant ring-width indices as predictors for examining Prairie drought. Although the difference in amount of variance explained by the LW and RW reconstructions is minimal, it does provide evidence that LW can be used as a proxy for climate variables. Adjusting for the inter-correlation with earlywood-width may prove useful as an improvement to increase the signal retained in the LW chronologies [19], and should be investigated further.

This preliminary study using LW as a proxy for climate variability suggests that the geographical expansion of coverage by LW chronologies and further development of statistical methods may lead to successful reconstructions of indices of synoptic-scale drought, other than PDSI, such as the El Niño/Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), patterns that influence the climate of the Prairie region. Further research to establish a network of *Q. macrocarpa* chronologies in this region of few dendroclimatic records, will contribute to a better understanding of the regional climate variability.

Acknowledgments

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