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A dendroclimatological assessment of shelterbelt trees in a moisture limited environment

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ABSTRACT

The goal of this paper is to apply dendroclimatological methods to the analysis of two commonly planted shelterbelt tree species, *Fraxinus pennsylvanica* (green ash), and *Picea glauca* (white spruce), to assess their current relationship with climate and determine how their growth may be affected by climate change in the moisture limited region of southeastern Saskatchewan. Spring precipitation and more importantly spring drought, as represented by the standardized precipitation evapotranspiration index (SPEI), were found to be the most important factors controlling the growth of green ash and white spruce in southeastern Saskatchewan. Furthermore, a breakdown in the radial growth-climate relationship was observed in individuals planted far from their typical native ranges, a potential indication of climate induced stress. Considering these findings, and projections of future climate, it is suggested that conditions beyond the northern limit of the artificial green ash range, and into the boreal forest, may become more suitable for green ash growth, while the southern limit of the artificial white spruce range is expected to recede northward. This information can help guide the management of shelterbelt systems in the Canadian Prairies to ensure they provide maximum practical and ecological benefits for now and into the future.

1. Introduction

Agroforestry has been gaining mainstream popularity, yet it has been common practice in the Canadian Prairies since 1901, when the Prairie Farm Rehabilitation Administration (PFRA) began providing free seedlings to landowners in the Prairie Provinces (Agriculture and Agri-Food Canada, 2008). This initiative has been an indispensable resource for landowners who wish to install shelterbelts to help cope with the harsh environment of the open prairie. Since the shelterbelt program began, over 600 million trees have been delivered, providing benefits such as protection from high wind, erosion, and snow retention, all of which have been associated with an increase in crop yields (Kort, 1988; Agriculture and Agri-Food Canada, 2008).

Although the numerous practical benefits of shelterbelts have long been understood, there remains an increasing need to recognize their associated ecological benefits. In their latest assessment report, the Intergovernmental Panel on Climate Change discussed the advantages of agroforestry as a tool to mitigate further climate change (IPCC, 2014). In over 100 years of service, an estimated 218 megatons of carbon dioxide have been removed from the atmosphere and stored in plant biomass thanks to the Canadian Shelterbelt Program (Agriculture and Agri-Food Canada, 2008). Prairie shelterbelts also represent an efficient and crucial form of adaptation needed to help bolster food security (Verchot et al., 2007; IPCC, 2014), and protect biodiversity (Guo, 2000), during climatically turbulent times. While this type of agroforestry can be considered as a serious option for future GHG mitigation and climate change adaptation (IPCC, 2014), shelterbelts are also vulnerable to the same changes they mitigate against. It is therefore important to gauge the internal resilience of shelterbelt systems to climatic change, to ensure that shelterbelts planted today will continue to offer their numerous associated benefits. As a first step, it is important to understand how tree growth is currently being affected by climate and how this is expected to change.

The effects of climate change are becoming increasingly widespread and are now of global concern (IPCC, 2013). Stress is placed on entire populations requiring them to adjust to the changes, with ecological communities being forced to either move to an area with more favorable conditions, or to rapidly evolve as a form of adaptation (Hoffmann and Sgrò, 2011). Trees on the other hand cannot simply move if they encounter some form of environmental limitation. Native range boundaries must therefore

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shrink or shift, and by doing so, currently established individuals will perish if they cannot adapt to a rapid shift in climate (McKenney et al., 2007; Woodall et al., 2009; Thomas, 2010). The province of Saskatchewan, and its legacy of shelterbelt trees, provides a unique platform where the spatial reach of certain tree species extends far past their typical native ranges, both northward and southward.

Dendroclimatology is a tool used to study past and present climates by statistically matching annually dated tree-ring chronologies with instrumental climate data (Kaennel and Schweingruber, 1995). This technique provides insight into how climate has impacted radial growth over a tree's lifetime. By utilizing a form of correlation function analysis, it is possible to determine the main climatic factors that are driving radial tree growth, such as temperature, and precipitation, with approximately monthly resolution (Biondi and Waikul, 2004). Tree growth is commonly driven by one (or a small subset) of these two factors, depending on whether the species in question is more sensitive to precipitation or temperature.

Much of southern Saskatchewan lies within the Palliser's Triangle, a region known for its aridity. Mean annual precipitation in Saskatchewan is 395 mm with values increasing in a southwesterly (~325 mm) to northeasterly (~475 mm) direction across the region. Of this annual total, approximately 70–80% falls as rain with June and July being the wettest months (20–35% of the annual total) (McGinn, 2010). In this area, it is common to have levels of evaporation that exceed the total annual amount of precipitation, leading to an overall moisture deficit (Lemmen and Dale-Burnett, 1999). Considered as the driest part of the Canadian Prairies, the triangle delineates a mixed grassland ecoregion that has long been plagued by the common occurrence of droughts. Palliser's Triangle has been host to several large-scale drought events throughout the 20th century, the most severe of which occurred in the 20′s, 30′s, and 1980′s (Lemmen and Dale-Burnett, 1999). In such an arid environment, it is likely that drought will be a limiting factor for many trees in the region.

The goal of this project is to apply dendroclimatological methods in the assessment of two commonly planted shelterbelt tree species, one coniferous, *Picea glauca* (white spruce), and one deciduous, *Fraxinus pennsylvanica* (green ash), to determine how their growth is being affected by climate in the moisture limited region of southeastern Saskatchewan. Due to the spatial extent of these planted shelterbelt trees that extend far past their typical native ranges (white spruce southward of its native range, and green ash northward of its native range), it is hypothesized that there exists a spatial boundary where the growth of these species becomes overly taxed due to being exposed to less than optimal growing conditions outside of their historical ranges.

2. Study sites

Two commonly planted shelterbelt species were chosen for this analysis based on the findings from Davis et al. (2013), who assessed the dendrochronological potential of nine commonly planted shelterbelt species based on their capacity to express a common growth signal, their sensitivity to climate, and their commonality. Green ash was ranked fifth in terms of its suitability for dendrochronological analysis but was chosen nonetheless due to its high inter-series correlation and environmental sensitivity, two characteristics that speak to its potential for climate analysis (Davis et al., 2013). Another desirable quality of green ash is its commonality, which is important when undertaking a study that is geographically widespread. Green ash is native to most of southern Canada east of Alberta, and extends northward towards the center of Saskatchewan. It is a fast growing, small to medium-sized tree that is relatively long lived, upwards of a hundred years (Hosie, 1969; Farrar 1995). Often used as third row in farmyard shelterbelts, and as a single row in field-shelterbelts, it is occasionally mixed with shrub species to provide increased height to rows of trees (Agriculture and Agri-Food Canada, 2007). Green ash is known to have a moderately high drought tolerance while it is less tolerant to flooding or excessive moisture (Herman et al., 1996).

White spruce was also chosen since it was ranked most useful for dendrochronological study among the nine shelterbelt species considered by Davis et al. (2013). This is due to its strong inter-series correlation and its high sensitivity to climate. White spruce is native to much of the forested regions in Canada and is found in every Canadian province. In Saskatchewan the white spruce range descends from the northern boreal forest and covers the upper two thirds of the province, leaving the remaining southern portion unrepresented. It is a slow growing medium sized tree that is long-lived, often up to two hundred years (Hosie, 1969; Farrar 1995). White spruce is commonly used as one of the inside two rows of a farmstead windbreak, and is rarely used in a field shelterbelt (Agriculture and Agri-Food Canada, 2007). Drought conditions impact the normal physiological functioning of white spruce, if severe enough, damage can occur at a cellular level and radial growth can be reduced. (Zwiazek, 1991; Barber et al., 2000).

A theoretical latitudinal transect was drawn east of Regina, SK, Canada, at about 103.5°W, with sites located at intervals of 0.5° latitude starting at the 49th parallel. Sampling occurred if the trees were a minimum of 50-years old and thus, potential sites were identified by selectively searching the PFRA's database for trees delivered pre-1960 to farms within the boundaries of the transect. Seven sets of 40 green ash samples and eight sets of 40 white spruce samples were drawn from shelterbelt systems along this transect, two samples from each tree, for a total of 600 cores (Fig. 1). The set interval of 0.5° and minimum age of 50-years was respected as much as possible with some minor deviations when sample sites could not be located at a given latitude, or when trees of an appropriate age could not be identified.

3. Methods

A 5.1 mm increment corer was used to extract sample cores from 13 distinct sample sites, seven of which contained living green ash trees (G1-G7), and eight, living white spruce trees (W1-W8). All sites, with the exception of one (Site G1), were sampled during the spring and summer of 2012. Site G1 was sampled the year prior, in the fall of 2011. Extracted samples were later glued to slotted mounting boards and sanded with progressively finer sandpaper: 80, 120, 220, 320, and 400 grit. The polished nature of these sanded samples made it possible to clearly view cell structure at a cellular level. Radial growth was measured using a Velmex stage system under a 63X Nikon stereomicroscope, with a precision of 0.001 mm.

The program COFECHA (Holmes, 1983; Grissino-Mayer, 2001) was subsequently incorporated to statistically cross-date the samples and fix an overall annual-growth pattern for trees within each site. By comparing each core to a site-specific master chronology, the program outputs a mean series inter-correlation (MSI) value, based on 30-year overlapping segments. COFECHA also flags individual chronologies that likely contain errors such as missed or false rings. The measurements are then checked until there are no remaining flags or until the MSI value is well above 0.4226, the minimum value for significance at the 99% confidence level (Grissino-Mayer, 2001). COFECHA also provides values for average mean sensitivity and autocorrelation. Average mean sensitivity is a measure of how responsive the tree is to its surrounding environment, while an autocorrelation value provides a measure of the degree to which previous year's conditions affect growth during the current growing season (Grissino-Mayer, 2001).

Fig. 1. A map of southern Saskatchewan with delineated ecoregions. Green ash samples were taken from sites denoted by an X and white spruce from sites denoted by a diamond. Climate stations used in the analysis are denoted by a triangle.

Resulting chronologies were standardized using ARSTAN version 41d (Cook and Krusic, 2005). The goal of standardization is to achieve a better representation of the trees response to its environment by eliminating biological and age-related growth trends. A fitted negative exponential curve was selected to detrend the ring width chronologies, this is a common choice since it best accounts for the natural age-related growth decline. At the end of the standardization process, a mean-value chronology is built, providing an overall site-specific growth signal that can be used for between site comparison and climate analysis. Overall, the applied sampling design and standardization techniques used in this study are designed to remove much of the between tree variability which can be caused by variability in microsite characteristics and an inconsistent response of individuals to certain biophysical drivers. Observations therefore involve the entire cohort and are made at the site level.

Green ash and white spruce correlation matrices were built to determine whether the trees at each site were responding to their environment in the same way as trees of the same species growing at neighboring sites, or whether there existed an observable difference in the radial-growth pattern between the sites along the transect. The Pearson's product moment correlation coefficient was used to compare radial growth sequences produced after standardization. The residual radial growth chronologies were chosen as they are believed to contain more internal variability associated with the climate signal when compared with standardized chronologies (Cook, 1985). Residual chronologies from each site were compared against those from all other sites for each species individually. The common growth interval between each pair was used during the correlation analysis to retain the maximum amount of information. Values for correlation were significant if they surpassed the critical value at the 95% confidence interval.

Two data sets are incorporated to determine the climatic relationships with tree growth. First, homogenized mean monthly temperature and adjusted total monthly precipitation data from long term climate stations in Melfort, Pilger, Kelliher, Indian Head, Yellow Grass, and Estevan (see locations on Fig. 1) were obtained from Environment Canada's Adjusted and Homogenized Canadian Climate Data (AHCCD) set. For these data, temperature homogeneity problems caused by station relocation and changes to instrumentation and observing practices have been addressed while precipitation values were adjusted for known measurement issues such as wind undercatch, evaporation, and wetting loss (Mekis and Vincent, 2011; Vincent et al., 2012). As a result, these values represent the best available data over the study region.

Due to the arid nature of the study area, it is important to take a moment to carefully consider the quantification of drought.

Many drought indices have been created, with perhaps the most well-known being the Palmer Drought Severity Index (PDSI) developed by Palmer (1965). This index takes into account precipitation, evapotranspiration, runoff, and soil moisture conditions. Although comprehensive, its calculation is quite complex, is fixed to the monthly time scale, and has been critiqued for using potentially false assumptions regarding water balance (Alley, 1984). The Standardized Precipitation Index (SPI) was developed by McKee et al. (1993) to provide a better representation of drought than the PDSI with a more flexible time scale. More specifically, it can be computed for any length of time specified by the user (e.g., 1, 3, 6-month etc.). This method is essentially a standardized index that provides a representation of the probability of a precipitation deficit over a given period of time. The computation of this index is based solely on instrumental precipitation data (Guttman, 1998). Therefore, the SPI is dependent on the quality and length of the precipitation record since this is the only data source taken into consideration (Guttman, 1998; Wu et al., 2005).

A newer measure of drought is the Standardized Precipitation-Evapotranspiration Index (SPEI). It was developed by Vicente-Serrano et al. (2010) and combines the needed temperature and evaporation detail captured by the PDSI, with the simplicity and flexibility of the SPI (Vicente-Serrano et al., 2010). The SPEI is perhaps the best measurement of drought for the purpose of this study, since the main drivers of tree growth (temperature and precipitation), are both adequately considered and can be computed over a flexible time scale. Since SPEI are not available from the AHCCD set, the gridded one-month SPEI used in Bonsal et al. (2017) were used to assess relationships with drought. These SPEI were derived using monthly temperature and precipitation input from the Canadian CANGRD data set. CANGRD values were interpolated to a 50 km grid using climate stations from the aforementioned AHCCD set.

DendroClim2002 (Biondi and Waikul, 2004), a program commonly used in dendrochronology for correlation function analysis, was employed in this study. Site specific standardized master growth chronologies, were input against temperature, precipitation, and SPEI data independently. The correlation function analysis, which helps to assess the strength of the relationship between radial tree-growth and monthly climate variables, was run over two full growing seasons, yet the period of April to September from both the previous and current growth years (year n and year n-1) was of most interest in this study. Temperature and precipitation data from the nearest aforementioned climate station was used in the analysis of each individual site. Similarly, SPEI data were taken from the grid cell nearest each site. In several cases, the radial growth chronologies were shorter than the instrumental climate records. The relationship between radial-growth and monthly climate was therefore assessed over the full length of the ring width records when possible (Tables 1 and 2). The SPEI dataset was very complete, the growth climate relationship was therefore assessed over the full length of the ring width records in all cases (SPEI correlation function analysis segment length = chronology length − 1). The output from the DendroClim2002 analysis is representative of the trees' radial growth sensitivity to either temperature, precipitation, or SPEI.

4. Results

The seven green ash site chronologies displayed an average length of 65 years, with an average tree core length of 53 years (Table 1). All chronologies demonstrated a very high series intercorrelation r-value, averaging 0.676, well above the minimum required value of 0.4226 for significance at the 99% confidence interval based on 30-year overlapping segments (Grissino-Mayer 2001). Values for average mean sensitivity as well as for autocorrelation were also high throughout the chronologies, displaying an average of 0.315 and 0.619 respectively (Table 1).

The eight white spruce chronologies had a shorter average length of 58 years, with an average tree core length of 51 years (Table 2). All chronologies had an even higher series intercorrelation r-value, with an average of 0.744, again using 30-year overlapping segments. The average mean sensitivity and autocorrelation values were also slightly higher than with green ash, averaging 0.352 and 0.718 respectively (Table 2).

The cross-correlation matrices demonstrated a dynamic relationship between site-specific residual master growth chronologies, generally displaying fewer significant correlations in and among sites with trees planted far from their typical native ranges. Correlation coefficients associated with the green ash correlation matrix varied from −0.115 to 0.739 (Table 3). This range was slightly smaller for white spruce, with associated r-values between −0.102 to 0.691(Table 4). In both cases the individual correlation matrices each illustrated a distinct pattern that separates the sites into two distinct groups (Table 3 and 4).

Among the green ash, there was a clear distinction between the four southernmost sites and the three northernmost sites, where the trees located in the north no longer significantly correlate with the majority of those in the south, nearer the green ash native range. The second northernmost site (G2) was an exception, as the growth signal correlated significantly to those from all of the other sites except for the two nearest itself (Table 3).

Among the white spruce sample sites, a similar distinction was found between the six sites located in the north (W1–W6), and the two southernmost ones (W7 and W8); again marking a separation between two distinct groups of chronologies that do not

Table 1
Green ash study site and resulting site-specific chronology information. Chron. Length = Chronology length, Seg. Used for PCFA = Segment used for precipitation correlation function analysis, Auto Corr. = Auto correlation: indicates the effect of previous year's growing conditions on current year's growth. AMS = Average mean sensitivity: demonstrates mean year-to-year variability of radial growth within the chronology. MSI = Mean series intercorreltion: indicates the strength of correlation between samples taken from the same location, based on 30-year overlapping segments.

Site	Latitude	Longitude	Chron. Length	Seg. Used for PCFA	Avg. Age of Trees	Auto Corr.	AMS	MSI
G1	52°08′06.1”	103°24′26.9”	60 yrs. (1951–2010)	56 yrs. (1952–2007)	47.2 yrs.	0.732	0.318	0.594
G2	51°18′59.6”	103°38′09.1”	57 yrs. (1955–2011)	55 yrs. (1956–2010)	51.4 yrs.	0.683	0.263	0.728
G3	51°08′09”	103°35′49.6”	56 yrs. (1956–2011)	54 yrs. (1957–2010)	48.7 yrs.	0.635	0.299	0.653
G4	50°34′17.1”	104°03′46.9”	76 yrs. (1936–2011)	74 yrs. (1937–2010)	61.8 yrs.	0.553	0.326	0.675
G5	49°50′18.7”	103°25′52.3”	66 yrs. (1946–2011)	65 yrs. (1947–2011)	50.7 yrs.	0.637	0.274	0.608
G6	49°26′08.2”	103°18′51.7”	75 yrs. (1937–2011)	74 yrs. (1938–2011)	58.0 yrs.	0.523	0.345	0.726
G7	49°10′30”	103°35′12.1”	62 yrs. (1950–2011)	61 yrs. (1951–2011)	50.0 yrs.	0.569	0.377	0.746
Avg.	NA	NA	64 yrs.	63 yrs.	52.5 yrs.	0.619	0.315	0.676

Table 2
White spruce study site and resulting site-specific chronology information. Chron. Length = Chronology length, Seg. Used for PCFA = Segment used for precipitation correlation function analysis, Auto Corr. = Auto correlation: indicates the effect of previous year's growing conditions on current year's growth. AMS = Average mean sensitivity: demonstrates mean year-to-year variability of radial growth within the chronology. MSI = Mean series intercorreltion: indicates the strength of correlation between samples taken from the same location, based on 30-year overlapping segments.

Site	Latitude	Longitude	Chron. Length	Seg. Used for PCFA	Avg. Age of Trees	Auto Corr.	AMS	MSI
W1	52°41′50.2”	104°53′05.9”	65 yrs. (1947–2011)	60 yrs. (1948–2007)	58.9 yrs.	0.720	0.373	0.754
W2	51°57′40.8”	103°47′58.0”	67 yrs. (1945–2011)	57 yrs. (1954–2010)	56.3 yrs.	0.746	0.342	0.744
W3	51°43′54.9”	103°50′38.4”	64 yrs. (1948–2011)	57 yrs. (1954–2010)	55.5 yrs.	0.718	0.330	0.696
W4	51°07′29.6”	103°38′36.3”	59 yrs. (1953–2011)	57 yrs. (1954–2010)	53.7 yrs.	0.817	0.300	0.761
W5	50°34′17.1”	104°03′46.9”	62 yrs. (1950–2011)	60 yrs. (1951–2010)	56.7 yrs.	0.810	0.270	0.797
W6	49°50′18.7”	103°25′52.3”	66 yrs. (1946–2011)	65 yrs. (1947–2011)	58.0 yrs.	0.786	0.374	0.712
W7	49°23′29.3”	103°22′09.3”	37 yrs. (1975–2011)	36 yrs. (1976–2011)	33.3 yrs.	0.582	0.394	0.764
W8	49°08′42.7”	104°18′01.7”	42 yrs. (1970–2011)	41 yrs. (1971–2011)	34.8 yrs.	0.562	0.430	0.726
Avg.	NA	NA	58 yrs.	54 yrs.	50.9 yrs.	0.718	0.352	0.744

Table 3
Green ash correlation matrix using the Pearson product moment correlation coefficient, illustrating the strength of the relationship between all sites based on common intervals shared between each pair. Shaded cells represent significance above the 95% confidence interval.

Site	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**
G1	**1.0000**	0.0572	**0.5046**	-0.1153	0.0263	0.1410	0.0122
G2	0.0572	**1.0000**	0.0115	**0.4857**	**0.5143**	**0.4190**	**0.4367**
G3	**0.5046**	0.0115	**1.0000**	-0.0521	**0.2751**	0.2108	0.1956
G4	-0.1153	**0.4857**	-0.0521	**1.0000**	**0.5705**	**0.2865**	**0.4030**
G5	0.0263	**0.5143**	**0.2751**	**0.5705**	**1.0000**	**0.7393**	**0.6178**
G6	0.1410	**0.4190**	0.2108	**0.2865**	**0.7393**	**1.0000**	**0.7240**
G7	0.0122	**0.4367**	0.1956	**0.4030**	**0.6178**	**0.7240**	**1.0000**

Table 4
White spruce correlation matrix using the Pearson product moment correlation coefficient, illustrating the strength of the relationship between all sites based on common intervals shared between each pair. Shaded cells represent significance above the 95% confidence interval.

Site	**W1**	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**
W1	**1.0000**	**0.5119**	**0.4418**	**0.3886**	**0.4521**	**0.3211**	0.1700	0.0024
W2	**0.5119**	**1.0000**	**0.5788**	**0.5059**	**0.6906**	**0.5524**	-0.1017	0.3046
W3	**0.4418**	**0.5788**	**1.0000**	**0.5720**	**0.6424**	**0.4522**	0.1328	0.2373
W4	**0.3886**	**0.5059**	**0.5720**	**1.0000**	**0.5747**	**0.5381**	0.0706	0.0981
W5	**0.4521**	**0.6906**	**0.6424**	**0.5747**	**1.0000**	**0.6166**	0.1752	**0.3822**
W6	**0.3211**	**0.5524**	**0.4522**	**0.5381**	**0.6166**	**1.0000**	0.0154	**0.4113**
W7	0.1700	-0.1017	0.1328	0.0706	0.1752	0.0154	**1.0000**	0.1964
W8	0.0024	0.3046	0.2373	0.0981	**0.3822**	**0.4113**	0.1964	**1.0000**

significantly correlate with each other. The more strongly associated sites, were again found closer to the white spruce native range to the north (Table 4). In this case, the growth signals from the two southernmost sites show no significant relationship with nearly all of the other chronologies.

For green ash, the correlation function analysis using mean monthly temperature and total monthly precipitation revealed a significant relationship between radial growth and spring precipitation (May-June) from the previous growth season (n-1) (Fig. 2A). There was no consistent pattern of significant relationships between radial growth and precipitation from the current growth season (year n). While June precipitation from year n-1 remained significantly important in all but one site (G3), May precipitation, which was also significant in all but one site (G1), demonstrates decreasing influence in a northerly direction. Two of the green ash sites (G2 and G6) were also significantly correlated with April precipitation from year n-1. Site G3, is the only site that did not significantly correlate with June precipitation from the previous growing season. Results from the temperature correlation function analysis revealed no consistent significant relationships, suggesting that temperature alone was not a significant factor for green ash growth in this region. Temperature results for green ash were therefore excluded from further study

The results from the green ash SPEI correlation function analysis were similar to those from the green ash intraspecies correlation matrix. A clear shift can be seen between the third northernmost site (G3) and the sampling site to the immediate south (G4), where spring drought from year n-1 goes from being a significant predictor of growth in the south of the province to becoming less important northward of site G4 (Fig. 2C). Several of the green ash site chronologies (five of seven) revealed a significant and positive correlation with SPEI during the months of May and June and four of seven sites revealed a positive relationship with SPEI from earlier in the spring during the month of April. A positive relationship with SPEI indicates a more successful growing season in terms of ring development during years with sufficient moisture availability and vice versa. Site G2 can once again be considered as an outlier in this case since the relationship between green ash radial growth and SPEI at this site is more similar to that of green ash growing further south.

For white spruce there were no consistent significant relationships between the radial growth of this species and precipitation from the previous growth season (year n-1). However, the correlation function analysis did reveal a strong relationship with spring precipitation during the month of June from the current growing season (Fig. 2B). While six of the eight site chronologies demonstrated a significant relationship with this climate variable, two of the southernmost sites (W6 and W7) showed no such relationship. Correlation with June precipitation fluctuated from 0.36 to 0.47 among the northern sites with a sharp decline from 0.40 to 0.20 between sites W5 and W6. Results from the temperature correlation function analysis for white spruce were also inconclusive and revealed no consistent significant relationships.

The SPEI correlation function analysis clearly illustrated the importance of drought in June of the current growing season (Fig. 2D). For white spruce, June SPEI is significantly correlated to radial tree growth in all but one site, the second southernmost site (W7). The decrease in the significance of June drought between sites W6 and W7 coincides with the observed breakdown in the common growth signal observed in the white spruce correlation matrix.

5. Discussion

The consistent moderate to high values for average mean sensitivity in both green ash and white spruce, 0.314 and 0.352 respectively (Tables 1 and 2), are consistent with the findings from Davis et al. (2013), and further confirms that these species are sensitive to environmental inputs. Moreover, the results from this study suggest that green ash may hold more dendrochronological potential than originally anticipated. The climatic influence of green ash, as measured by the R-squared value associated with a single predictor variable, in this case June precipitation or May SPEI, are upwards of 0.40 and 0.35 in this analysis, rivaling the top contenders for climatic influence from the Davis et al. (2013) study.

Our results reveal that in both species-specific cases, groups of trees growing far beyond their typical native ranges do not correlate well suggesting that radial-growth within these distinct sites is being affected by differing, regionally defined, environmental characteristics. It has been suggested that climatic stress can lead to instability in the growth-climate relationship over time (Büntgen et al., 2006; Oberhuber et al., 2008). Since green ash is a drought tolerant species native to southern Saskatchewan (Herman et al., 1996), it is well adapted in this portion of the province and will react in a predictable manner to existing environmental characteristics. But when its range is pushed northward, these trees become more stressed, as they must cope with unfavorable environmental factors such as the amount and timing of excessive moisture.

Conversely, white spruce, which is not as tolerant to drought, has a historical range that does not extend far from the limits of the northern boreal forest. Shelterbelt-white spruce that are planted southward in more drought prone regions are exposed to stressful conditions that are similarly difficult for them to cope. In extreme cases, trees will die if planted in areas where unfavorable conditions exist beyond physiological limitations, or if environmental conditions become unfavorable due to a shift in climate (Woodall et al., 2009). In fact, white spruce samples were drawn from the two southmost sites (W7 and W8) regardless of their limited age due to the difficulty of finding living white spruce trees in this portion of the province. The white spruce growing within these two sites exhibit higher values for mean sensitivity and lower auto correlation values, both characteristic of an observed response to drought stress (Rigling et al., 2002).

The reason that green ash is driven primarily by conditions from the previous year (year n-1), and white spruce by conditions during the current year (year n), is likely due to leaf out at the beginning of the growing season. Green ash has a tendency to leaf out late compared with other deciduous tree species growing in close proximity. They are therefore required to store up a significant amount of photosynthate each year for the long leafless period at the beginning of each growing season. Conversely, as an evergreen, white spruce trees are fully equipped to begin photosynthesizing at the beginning of the growing season.

The correlation function analysis, comparing variations in green ash growth and climate (Fig. 2A), reveals that May and June precipitation from year n-1 remained significantly and positively correlated with green ash radial-growth in all but one site respectively. While June precipitation remains consistently important, May precipitation illustrates a decrease in influence in a northerly direction. This suggests that there is a decreasing need for moisture at the higher latitude sites in the province. May precipitation from year n-1 is most important at the three southernmost sites (G5–G7), where precipitation is more scarce and where the green ash require extra moisture to store up enough energy for the beginning of the next growing season. North of the Palliser's Triangle, May precipitation becomes less and less important as moisture becomes more readily available, trees located at higher latitudes are not as pressured to store energy for the next growing season and therefore the energy stored from June precipitation is enough to initiate early-wood growth.

The SPEI accounts for fluctuations in temperature while considering evaporation demand, while it was not immediately apparent

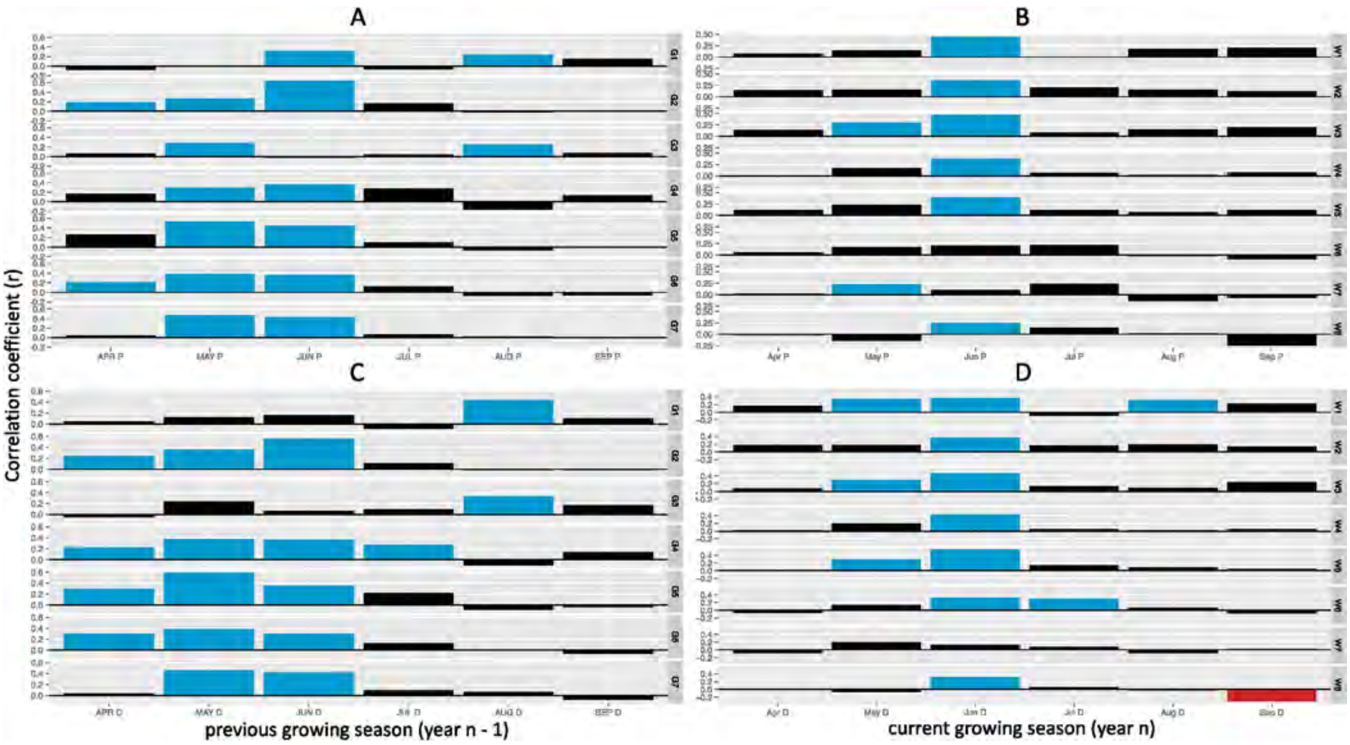

Fig. 2. Correlations between: green ash radial-growth and monthly precipitation (A), white spruce radial growth and monthly precipitation (B), green ash radial-growth and monthly SPEI (C), white spruce radial-growth and monthly SPEI (D). precipitation data was taken from the nearest climate station, while gridded 1-month SPEI data, provided by Environment Canada, was taken from the nearest grid cell to each site. Blue bars represent a positive relationship, and red bars a negative relationship, both significant above the 95% confidence interval, black bars represent non-significance. Green ash radial growth was driven by conditions during the previous growing season (year n-1), while white spruce was driven by conditions during the current growing season (year n). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that temperature was an important factor limiting the growth of these trees, it is clearly an underlying factor that can in fact affect soil moisture and in turn significantly influence radial growth. In the case of white spruce, all but one site (W7) responded significantly to June SPEI (Fig. 2D). It is well known that the growth of this species is negatively impacted under drought conditions (Zwiazek, 1991; Barber et al., 2000), and that instability in the growth-climate relationship can result from increased stress (Büntgen et al., 2006; Oberhuber et al., 2008). This leads to the assumption that the observed breakdown in the growth-climate relationship between sites W6 and W7 is directly related to an increase in drought stress in this southern part of the province (Fig. 3)

Shelterbelts systems represent an anthropogenic modification of the prairie landscape. These agroforestry systems are heavily influenced by and rely on human intervention for initial establishment, and at times for ongoing stand success. In certain cases, landowners have indicated that they actively care for and maintain their shelterbelts (Rempel, 2014). This provides a possible explanation as to why site G2 is identified as an outlier in terms of its response to climate. It would be expected that the trees at this site would behave differently than those at neighboring sites if given a competitive advantage (Fig. 3). It is important to keep in mind that shelterbelts are not governed by traditional forest dynamics, there is little to no natural regeneration, all trees are of the same cohort and it is extremely unlikely that they would be exposed to natural disturbance such as fire and insect damage. The most important external forces, beyond human intervention, are therefore climate related. This remark lends further weight to the suggestion that the observed variability in the tree-ring records are associated with climate, and in this case drought. This is further demonstrated in Fig. 3, where significant negative departures from average annual radial growth consistently correspond with drought conditions, as represented by the SPEI.

Climate has always been the main influence on the location of species boundaries, with established individuals residing within areas that are climatically suitable for their ongoing existence (McKenney et al., 2007; Woodall et al., 2009; Thomas, 2010; Mood, 2013). Past studies regarding climate change in the prairies illustrates that while overall precipitation is expected to increase in certain areas of Saskatchewan, the concurrent increase in temperature will result in reductions to soil moisture and a subsequent increase in the frequency and intensity of drought (Herrington et al., 1997; Sauchyn and Kulshreshtha, 2007). Since drought was consistently revealed as the most important factor controlling the growth of green ash and white spruce in Saskatchewan, climate change will likely have a profound impact on the growth and extent of these two species. An increase in drought would likely cause the white spruce planted in southern shelterbelts to suffer, causing the current artificial range to retreat towards the boreal forest in the north of the province. For green ash on the other hand, which is given a competitive advantage due to its drought tolerance (Herman et al., 1996), it is possible for the current artificial range to expand northward, towards, and eventually reaching into the current boreal forest edges (e.g., Thorpe et al., 2006).

6. Conclusion

In this paper, we report on an observed breakdown in the radial growth-climate relationship of two commonly planted shelterbelt trees. It is hypothesized that this breakdown is due to climatic stress, with trees planted far outside their typical native ranges, in zones where sub-optimal growing conditions exist. While there was no direct evidence of radial growth decline or senescence

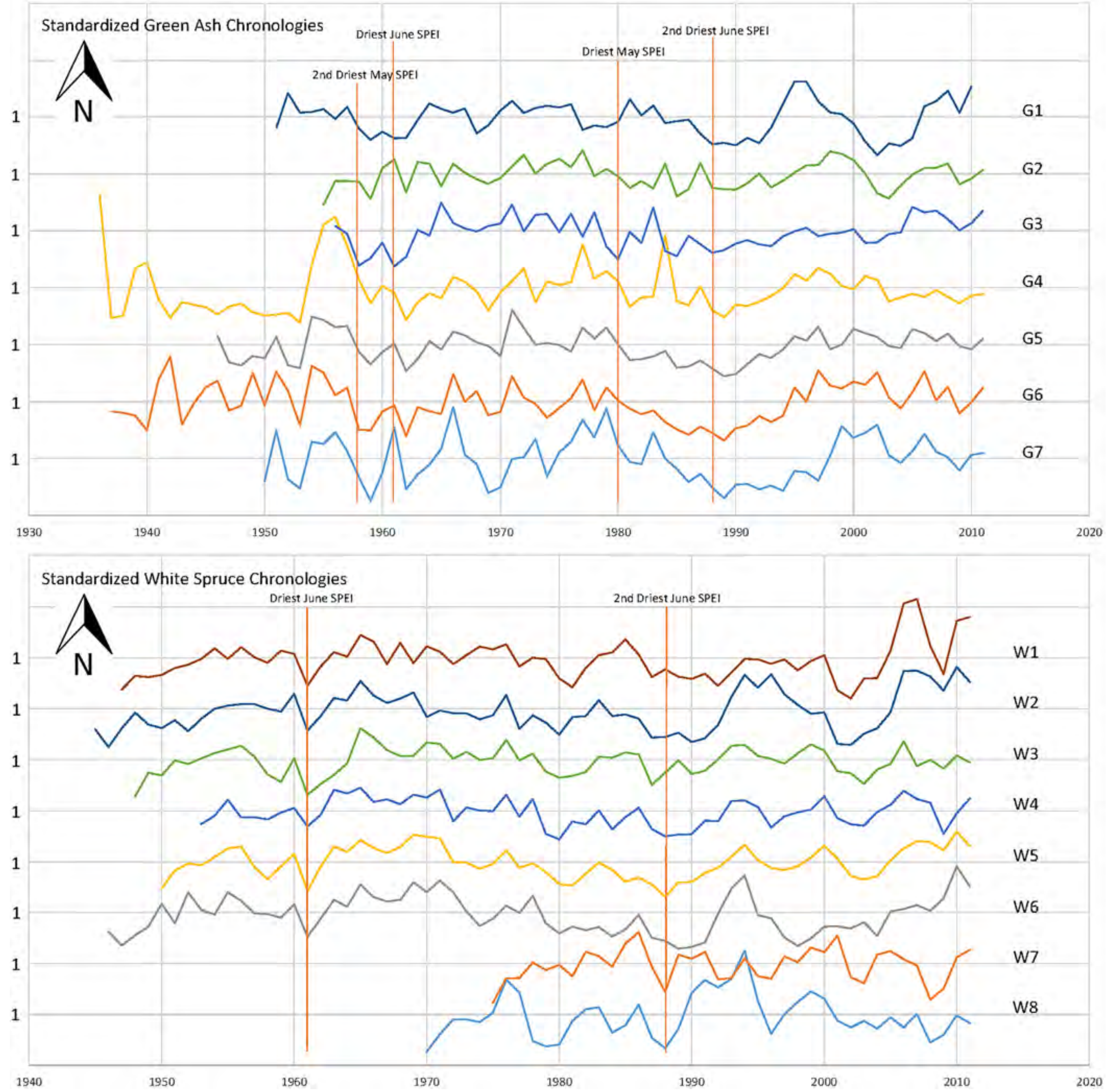

Fig. 3. A pair of graphs representing standardized green ash and white spruce growth over time. Each chronology is presented as an index that varies around a mean of one. Any value above one (above each respective line) represents a larger than average ring, and anything below represents a smaller than average ring. Chronologies are arranged from north to south from top to bottom. The red labeled perpendicular lines represent noteworthy occurrences of drought (the most extreme negative SPEI values), taken from a mid-point within our gridded 1-month SPEI database. SPEI was identified as the most significant predictor variable impacting the growth of these two species, for green ash, May and June SPEI, and for white spruce, June SPEI only. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

within the sampled trees in our experimental transect, we are confident that if a wider sampling net were cast, such evidence could be found nearest the margins. This was unfortunately outside the scope of this research and should be the focus of future scientific inquiry, along with a more extensive investigation of the mechanisms behind the observed shift in the radial growth-climate relationship.

Dendroclimatological analyses provided an indication of the possible regions where conditions become sub-optimal for green ash and white spruce growth in Saskatchewan. It was also found that, for different reasons, drought is the most important factor controlling the growth of both species in Saskatchewan. Green ash was found to be more tolerant to drought than excessive moisture, and so it is likely that wetter conditions are impacting the normal growth of this species northward of about 51° north latitude. An opposite effect can be seen in the white spruce population. By being less tolerant to drought, it is likely that drought conditions are impacting the normal growth of this species southward of 50° north latitude. When considering the possible intensification of drought in the area, it is likely that the southern boundary for white spruce will recede northward, while the current northern boundary for green ash optimal growth could expand toward the north into the boreal.

Those who rely on shelterbelts for their numerous associated benefits should be aware of climatic restrictions on shelterbelt trees. As demonstrated by this study, not all species of tree commonly used in shelterbelts are universally appropriate across the prairie landscape, especially considering that each species of tree responds to climate differently. Based on the findings from this paper, planters should avoid introducing white spruce in southern Saskatchewan. As for green ash, which could be given a competitive advantage in drier environments, this species may be better suited for the future climate of Northern Saskatchewan. Further research is needed to identify similar margins and restrictions for other commonly planted shelterbelt trees.

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References

Agriculture and Agri-Food Canada, 2007. Trees and Shrubs for Prairie Shelterbelts (http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1192201777018 Accessed 28 Feb 2013).

Agriculture and Agri-Food Canada, 2008. Circling the Globe with Trees (AAFC No. 10772E).

Alley, W.M., 1984. The Palmer drought severity index: limitations and assumptions. J. Clim. Appl. Meteorol. 23, 1100–1109.

Büntgen, U., Frank, D.C., Schmidhalter, M., Neuwirth, B., Seifert, M., Esper, J., 2006. Growth/Climate response shift in a long subalpine spruce chronology. Trees 20, 99–110.

Barber, V.A., Juday, G.P., Finney, B.P., 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature 405, 668–673.

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

Bonsal, B.R., Cuell, C., Wheaton, E., Sauchyn, D.J., Barrow, E., 2017. An assessment of historical and projected future hydro-climatic variability and extremes over southern watersheds in the Canadian Prairies. Int. J. Climatol. (in print).

Cook, E.R., Krusic, P.J., 2005. ARSTAN v. 41d: A Tree-Ring Standardization Program Based on Detrending and Autoregressive Time Series Modeling, with Interactive Graphics. Tree-Ring Laboratory, Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, U.S.A.

Cook, E.R., 1985. A Time Series Analysis Approach to Tree Ring Standardization. Ph.D. Dissertation. University of Arizona, Tucson.

Davis, E.L., Laroque, C.P., Van Rees, K., 2013. Evaluating the suitability of nine shelterbelt species for dendrochronological purposes in the Canadian Prairies. Agrofor. Syst. 86, 1–15.

Farrar, J.L., 1995. Trees of the Northern United States and Canada. State University Press, Iowa.

Grissino-Mayer, H.D., 2001. Research report evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Res. 57, 205–221.

Guo, Q., 2000. Climate change and biodiversity conservation in great plains agroecosystems. Global Environ. Change 10, 289–298.

Guttman, N.B., 1998. Comparing the palmer drought index and the standardized precipitation index. Water Resour. Bull. 34, 113–121.

Herman, D.E., Craig, M.S., Vernon, C.Q., 1996. North Dakota Tree Handbook. North Dakota State University, North Dakota Forest Service, Bismarck,ND, pp. 58505.

Herrington, R., Johnson, B., Hunter, F., 1997. Responding to global climate change in the prairies. Canada Country Study: Climate Impacts and Adaptations, Vol. III. Environment Canada, Ottawa.

Hoffmann, A.A., Sgrò, C.M., 2011. Climate change and evolutionary adaptation. Nature 470, 479–485.

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

Hosie, R.C., 1969. Native trees of Canada. In: Native Trees of Canada, 7th ed.

IPCC(2013). Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report . Intergovernmental Panel on Climate Change-IPCC, C/O World Meteorological Organization, 7bis Avenue de la Paix, CP 2300 CH-1211 Geneva 2 (Switzerland).

IPCC (2014). Mitigation of Climate Change. Contribution of IPCC (2014). Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, USA.

Kaennel, M., Schweingruber, F.H., 1995. Multilingual Glossary of Dendrochronology. Paul Haupt AG Bern.

Kort, J., 1988. Benefits of windbreaks to field and forage crops. Agric. Ecosyst. Environ. 22, 165–190.

Lemmen, D., Dale-Burnett, L., 1999. The Palliser Triangle. Atlas of Saskatchewan. University of Saskatchewan, Saskatoon.

McGinn SM.(2010) Weather and Climate Patterns in Canada's Prairie Grasslands. Arthropods of Canadian Grasslands (Volume 1): Ecology and Interactions in Grasslands Habitats. Biological Survey of Canada. 105–119.

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. Proc. 8th Conf. Appl. Climatol. 17, 179–183.

McKenney, D.W., Pedlar, J.H., Lawrence, K., Campbell, K., Hutchinson, M.F., 2007. Potential impacts of climate change on the distribution of north american trees. Bioscience 57, 939–948.

Mekis, E., Vincent, L.A., 2011. An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada. Atmos. Ocean 49, 163–177.

Mood, B.J., 2013. Dendrochronology of White Spruce (*Picea Glauca* [Moench] Voss) in Southern Saskatchewan (BSc Thesis). Mount Allison University.

Oberhuber W, Kolfer W, Pfeifer K, Seeber A, Gruber A, Weiser G. (2008) Long-Term Changes in Tree-Ring -Climate Relationships at Mt. Patscherkofel (Tyrol, Austria) Since the Mid 1980. *Trees (Berl West)* 22: 31–40.

Palmer, W.C., 1965. Meteorological Drought. US Department of Commerce, Weather Bureau, Washington, DC, USA, pp. 58.

Rempel, J.C., 2014. Costs, Benefits, and Barriers to the Adoption and Retention of Shelterbelts in Prairie Agriculture as Identified by Saskatchewan Producers (MES Thesis). University of Saskatchewan.

Rigling, A., Bräker, O., Schneiter, G., Schweingruber, F., 2002. Intra-Annual tree-Ring parameters indicating differences in drought stress of *Pinus sylvestris* forests within the erico-Pinion in the valais (Switzerland). Plant Ecol. 163, 105–121.

Sauchyn, D., Kulshreshtha, S., 2007. Prairies. In: From Impacts to Adaptation: Canada in a Changing Climate., pp. 275–328.

Thomas, C.D., 2010. Climate, climate change and range boundaries. Divers. Distrib. 16, 488–495.

Thorpe, J., Henderson, N., Vandall, J., 2006. Ecological and Policy Implications of Introducing Exotic Trees for Adaptation to Climate Change in the Western Boreal. Saskatchewan Research Council, Saskatoon, Saskatchewan (Publication 11776-1E06).

Verchot, L., van Noordwijk, M., Kandji, S., Tomich, T., Ong, C., Albrecht, A., Mackensen, J., Bantilan, C., Anupama, K., Palm, C., 2007. Climate change: linking adaptation and mitigation through agroforestry. Mitigation Adaptation Strategies Glob. Change 12, 901–918.

Vicente-Serrano, S.M., Santiago, B., Juan, L.M.I., 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J. Clim. 23, 1696–1718.

Vincent, L.A., Wang, X.L., Milewska, E.J., Wan, H., Yang, F., Swail, V., 2012. A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis. J. Geophys. Res. 117, D18110.

Woodall, C.W., Oswalt, C.M., Westfall, J.A., Perry, C.H., Nelson, M.D., Finley, A.O., 2009. An indicator of tree migration in forests of the eastern United States. For. Ecol. Manage. 257, 1434–1444.

Wu, H., Hayes, M.J., Wilhite, D.A., Svoboda, M.D., 2005. The effect of the length of record on the standardized precipitation index calculation. Int. J. Climatol. 25, 505–520.

Zwiazek, J.J., 1991. Cell wall changes in white spruce (Picea glauca) needles subjected to repeated drought stress. Physiol. Plant. 82, 513–518.