Radial-Growth Forecasting and the Implications for Planning and Management in the Grand River Watershed of Ontario, Canada

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The first objective of this thesis was to predict the future success of selected tree species under low (B1, 550 CO_2 ppm) and moderate (A1B, 720 CO_2 ppm) climate change scenarios as defined in the Special Report on Emissions Scenarios (SRES). This was accomplished through the creation of radial-growth forecasts for eastern hemlock (*Tsuga Canadensis* (L.) Carr.), sugar maple (*Acer saccharum* L.), white spruce (*Picea glauca* (Moench.) Voss), and white pine (*Pinus strobus* L.) in the Grand River Watershed of Ontario, Canada. The forecasts were founded on historic growth-climate relationships between standardized regional dendrochronologies for each species and past climate data from the Guelph OAC weather station. These species-specific growth-climate relationships were then extended to 2100 using modeled climate data from the Third Generation Coupled Global Climate Model (CGCM3) to project radial-growth under both emissions scenarios. Results indicated that eastern hemlock radial-growth will remain stable throughout the 21st-century, sugar maple and white spruce growth will start to decline, and white pine growth will increase. While the radial-growth forecasts were limited by the length of the past climate data, the accuracy of the modeled climate data, and the number and type of variables used in the forecast model, the results were statically significant and strongly supported in the literature.

The second thesis objective was to assess the potential impact of the radial-growth forecasts on environmental planning policy and forest management strategy in the Grand River Watershed. Examples of how the forecasts could influence basic management strategies in the watershed were provided to display the conceptual linkages between the results and policy formulation. Next, the radial-growth forecasts were presented to four forest managers working in the watershed to gage the practical implications, perceptions and limitations of the radial-growth forecasting method. While the managers found the radial-growth forecasts interesting, they also noted that the results were of limited use since they could not account for other factors important to the future success of the study species, such as seedling dispersal and establishment rates, as well as the potential effects of pathogens, insects and invasive species. Therefore, it was recommended that future research should work to extrapolate the results of the radial-growth forecasts to other tree species and types in the region, as well as incorporate more variables into the models, so that more accurate and applicable growth projections could be constructed in the watershed.

Acknowledgements

Thanks to Ben Phillips, Colin Laroque and Andre Robichaud for providing assistance in the field and access to the equipment at the Mount Allison University Dendrochronology Laboratory. Without you this project would not have been possible.

Thanks to my supervisor, Roger Suffling, for navigating me through this process and being an excellent editor in crunch time. Your input, encouragement and patience have pushed me to become a better researcher and writer.

Thanks to Martin Neumann, Albert Hovingh, David Schmitt and Peter Kelley for granting me access to the old-growth forests you manage. The long dendrochronologies I was able to construct from your trees was the primary reason this project was successful.

Finally, thanks to my colleagues in the School of Planning. You have made this experience very fun and extremely smooth. Your advice and friendship will not be forgotten, and I wish you all the best in the future.

Dedication

To:
Mum and Dad for giving me the ability and opportunity to study at this level;

Colin Laroque for teaching me how to conduct and enjoy research;
And
Don and Jill Spratt for inspiring me to further my education

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CHAPTER 1: INTRODUCTION

Climate change threatens the health and stability of forested areas throughout the world. Increasing concentrations of atmospheric greenhouse gases have caused average global temperatures to rise by 0.74°C since 1900 (Intergovernmental Panel on Climate Change (IPCC), 2007a). Trees have responded through range shifts and alterations in the timing of key-life events (Higgins & Harte, 2007; Parmesan & Yohe, 2003; Root et al., 2003). Marked transformations in ecosystem functions, species interactions, population biology and the distribution of trees are expected to continue (Chapin et al., 2004; Melillo, Callaghan, Woodward, Salati, & Sinha, 1990; Schwartz, Iverson, & Prasad, 2001), as temperatures are projected to warm by an additional 1.8 to 4°C throughout the 21st-century (Intergovernmental Panel on Climate Change (IPCC), 2007a). These climate change scenarios are believed to be far beyond the natural adaptation abilities of most species (J. A. Malcolm, Markham, & Garaci, 2002; Scott & Lemieux, 2007; Solomon & Kirilenko, 1997), and fragmented landscapes hinder the migration of trees into climatically suitable regions (de Dios, Fischer, & Colinas, 2007; Higgins & Harte, 2007; Schwartz, 1993). Thus, the future survival of many tree species may rely on progressive policies and strategies to protect urban and rural forests (McKenney, Pedlar, Lawrence, Campbell, & Hutchinson, 2007; Pitelka, 1997); many of which are essential to the long-term sustainability of our communities.

In view of this knowledge, the purposes of this thesis were twofold. The first was to predict the future success of selected tree species, and the second to evaluate the potential implications of these results on regional planning policy and forest management strategy. To complete these tasks, radial-growth forecasts for four tree species common to the Grand River Watershed of Ontario, Canada were constructed using dendroclimatology. Next, the results were presented to forest managers working in the watershed to gain insight regarding the impact of the study. Consequently, the usefulness of the radial-growth forecasting method as a planning and management tool in the watershed was gauged, and future research was proposed.

To more easily disseminate these findings, the two thesis objectives were addressed as individual chapters. The first chapter discusses the methods and results of the radial-growth forecasting study, and is directed towards scientists interested in forest ecology and dendrochronology. The second chapter examines the planning and management implications of the radial-growth forecasting study in the Grand River Watershed, and offers suggestions for future research. The thesis concludes by summarizing the primary findings and implications of the entire research project.

CHAPTER 2: RADIAL-GROWTH FORECASTS OF *TSUGA CANADENSIS, ACER SACCHARUM, PICEA GLAUCA AND PINUS STROBUS* IN THE GRAND RIVER WATERSHED OF ONTARIO, CANADA

2.1 Introduction

Greenhouse gas concentrations in the atmosphere are projected to increase throughout the 21st-century, resulting in longer, warmer and drier growing seasons in Ontario (Pacific Climate Impacts Consortium (PCIC), 2007; Wotton, Martell, & Logan, 2003). Consequently, the moisture content of forest soil and vegetation will drop, shifting the climatic niches of individual tree species within the province (McKenney et al., 2007). During the last significant warming period (Hypsithermal interval, 5000-7000 years ago), trees could naturally move across the landscape to survive. Now they are constrained by land-use patterns and forest fragmentation (Higgins & Harte, 2007; Iverson, Prasad, & Schwartz, 1996; Peters, 1990; Schwartz, 1993). Accordingly, government agencies and researchers have recommended adaptation strategies, such as assisted migration and reforestation projects, to protect Ontario’s forested landscapes and environmentally sensitive areas (Office of the Auditor General, 2006; Parry, Hulme, Nicholls, & Livermore, 1998; Scott & Lemieux, 2007).

Interest in adaptation strategies has spurred research investigating the effects of climate change on the geographic ranges and climatic niches of flora. For instance, Mckenney, Pedlar, Lawrence, Campbell and Hutchinson (2007) studied the impacts of climate change on the ranges of 130 North American tree species. They estimated an average northward range shift of 330 to 700 Km depending on the dispersal model and climate change scenario used. These models are, however, too coarse to directly inform management decisions at the scales used by most planners, and they cannot account for the local genetic adaptations of forest trees to climate (Laroque, 2005; Morgenstern, 1996; Pilkey & Pilkey-Jarvis, 2007). As a result, recent literature has strongly promoted finer-scale research when planning for forested landscapes under dynamic climatic conditions (Millar, Stephenson, & Stephens, 2007; Pilkey & Pilkey-Jarvis, 2007; Scott, Malcolm, & Lemieux, 2002; Suffling & Scott, 2002).

To predict the success of or demise of individual tree species at the regional level, researchers have forecasted the radial-growth patterns of trees using dendroclimatology (Girardin, Raulier, Bernier, & Tardif, 2008; Laroque & Smith, 2003). In short, species-specific radial-growth forecasts are founded on growth-climate relationships using dated and measured tree-rings, as well as historical climate data. These relationships are then extended into the future using modeled climate scenarios. Thus one can forecast the radial-growth trends for each species. As a result, researchers are able to identify species that will experience higher or lower radial-growth rates under climate change. This is important, as trees facing climatic stress are more likely to succumb to competition, disease or insect attack (van Mantgem et al., 2009). Despite the potential usefulness of radial-growth forecasts, only two such studies have been carried out: One on Vancouver Island, British Columbia, Canada (Laroque & Smith, 2003) and the Duck Mountain Provincial Forest in Manitoba, Canada (Girardin et al., 2008).

Closely replicating the method described by Laroque and Smith (2003), this paper forecasts the radial-growth response of four tree species common to the Grand River

Watershed (42°51’ to 44°13’ N latitude, 80°56’ to 80°20’ W longitude) (Fig 2.1). In this instance, 11 tree-ring chronologies from 8 sites are used to establish species specific growth-climate relationships with historical climate data from the Guelph Ontario Agricultural College (OAC) weather station (43°31'12"N, 80°13'48"W, climate station identifier # 6143083) (Fig. 2.2). To approximate future radial-growth rates, these relationships are then extended to 2100 using future precipitation and temperature data derived from the Third Generation Coupled Climate Model (CGCM3) produced by the Canadian Center for Climate Modeling and Analysis (Flato & Boer, 2001; Flato et al., 2000). Individual species forecasts based on the Special Report on Emissions Scenarios (SRES) B1 (550 CO_2 ppm) and A1B (720 CO_2 ppm) emissions scenarios are presented (Intergovernmental Panel on Climate Change (IPCC), 2007a).

2.2 Study Site and Species

The Grand River Watershed (GRW) of southwestern Ontario, Canada drains 6965 Km^2, making it the largest direct drainage basin to Lake Erie in Canada. The main stream rises at 525 m asl and runs 300 Km to Lake Erie. In 2007, roughly 925,000 people resided within the watershed, most of whom live in the cities of Kitchener, Waterloo, Cambridge, Guelph and Brantford (Grand River Conservation Authority, 2007). Demographic forecasts released by the Province of Ontario to 2031 predict continued high growth and development for the major centers in the GRW (Province of Ontario, 2006). Consequently, the protection and management of the watershed and its resources have gained in importance as evidenced in recent planning documents (City of Waterloo, 2007; Regional Municipality of Waterloo, 2008).

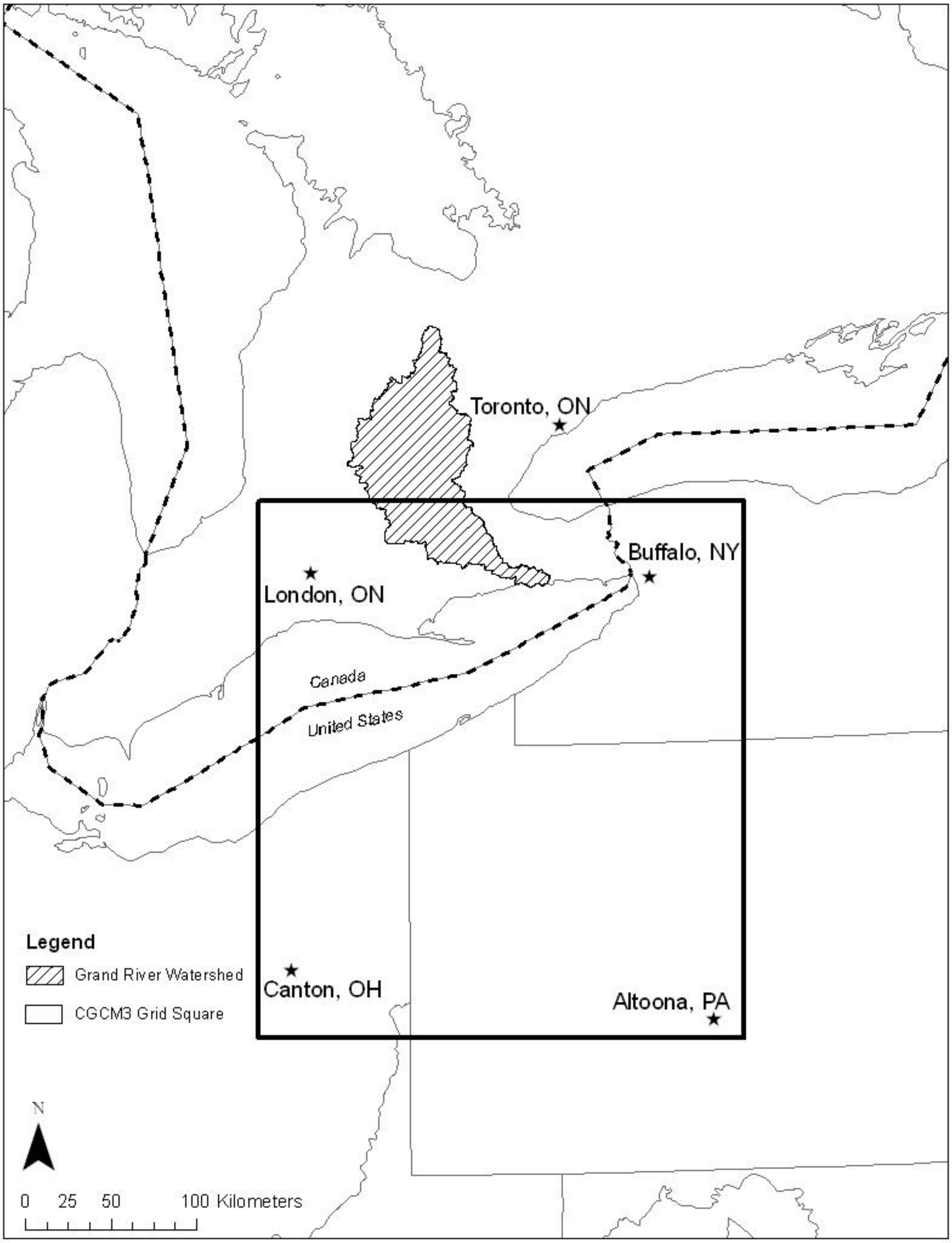


Figure 2.1 Location of the Grand River Watershed and the GCM square used in the study.

The GRW is particularly suitable for radial-growth forecasting, and of interest to ecologists, managers and planners, as it straddles the key ecological transition zone of two major forested regions in Ontario, the Great Lakes-St. Lawrence Forest and the North American Temperate Deciduous Forest (Neumann, 2009). Projections suggest that some tree species in the deciduous forest will migrate northward at the expense of species in the Great Lakes-St. Lawrence Forest as temperatures increase (J. Malcolm, Puric-Mladenovic, & Shi, 2004; Scott & Lemieux, 2007). This raises planning, policy and management questions regarding climate change effects on species in both regions. If appropriate information can be generated, then mitigation and adaptation needs can be defined and addressed (Hovingh, 2008).

The GRW is composed of 11 minor physiographic regions that include sand, till and clay plains, sand hills, drumlin fields, moraines, and ridges (Chapman & Putnam, 1984). The habitats in the northern sections of the study site are made-up of marshes, mixed deciduous-coniferous swamps, upland deciduous forest and agricultural lands. Eastern hemlock (*Tsuga Canadensis* (Carr.) L.), white pine (*Pinus strobus* L.), sugar and red maple (*Acer saccharum* L. and *Acer rubrum* L.), and some species common in the boreal forest, notably white spruce (*Picea glauca* (Moench) Voss), jack pine (*Pinus banksiana* (Lamb.)) and white birch (*Betula papyrifera* (Marsh.)), dominate the northern, Great Lakes-St. Lawrence Forest (Neumann, 2009). On the other hand, the southern region is comprised of Carolinian and slough forests, extensive marshes, floodplain meadows and oak savannas (Neumann, 2009). Sassafras (*Sassafras albidum* (Nutt.) Nees), hickory (*Carya spp.*(Nutt.)) and Walnut (*Juglans nigra* L.) are visible here, often found mixed with ash (*Fraxinus spp.* L.), maple (*Acer spp.*L.), oak

(*Quercus spp.*L.), and beech (*Fagus grandifolia* (Ehrh.)) forests (Neumann, 2009). According to the modified Guelph OAC weather dataset (see methods), the mean January, July and average annual temperatures in the GRW from 1881-2006 were 6.9°C, 19.8°C, and 6.7°C, respectively. Average annual precipitation over the same time period was 813mm.

Eastern hemlock, sugar maple, white spruce and white pine were the four species selected for the analysis. These species were chosen in consultation with managers from the Regional Municipality of Waterloo, the City of Kitchener and the Grand River Conservation Authority to ensure their significance within the study area. Significance was based on the ecological and economic role of each species in the GRW. Sugar maple was viewed as vital due to its considerable presence in parks throughout the area, as well as its role in the local maple syrup and timber industries. White pine and eastern hemlock were selected because of their abundance in remnant forests, especially along the river valleys. Finally, white spruce was chosen as a result of its vulnerability to predicted climate change, as it is positioned at the very southern extremity of its natural range in the GRW.

Tree-ring data for this project were collected at eight sites throughout the GRW using handheld increment boring tools to extract 430 cores (Fig. 2.2, Table 2.1). Selected sites were geographically separated from one another by at least 30 Km and contained the particular species of investigation in a mature dominant or co-dominant role. Sugar maple, eastern hemlock and white pine were each sampled at a minimum of three sites. For these species, twenty trees were selected at each site and cored twice at breast height (1.3 m) for a total of 40 cores per site. Cores were extracted at 90° from one another in level areas, and 180° from each other on steep slopes. Tree-ring data for white spruce were obtained from only nine trees (n=18) at one site due to the rarity of the species growing naturally in the GRW. To find sufficiently mature trees (>150 years) in this highly developed region, site differences such as slope, aspect, elevation and substrate were ignored. While these site-to-site differences likely contributed to variance in radial-growth rates, these were of no real concern as general climatic conditions and their relationship to radial-growth were the focus of this study.

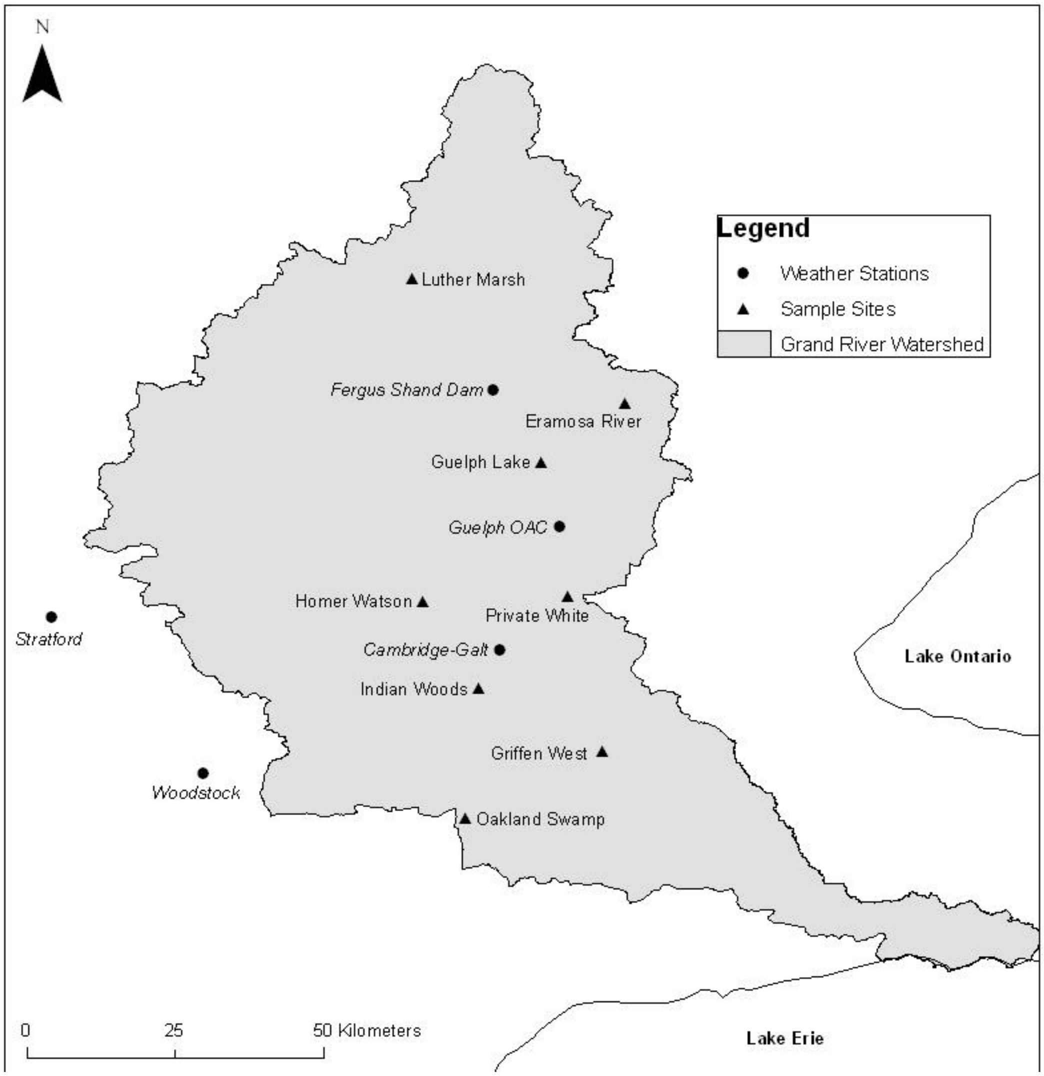


Figure 2.2 The 8 sample sites and 5 weather stations used in the study.

Table 2.1 The species sampled, elevations and locations of the eight study sites

No.	Name	Tree Species Sampled				Site description		
		Eastern Hemlock	Sugar Maple	White Pine	White Spruce	Latitude	Longitude	Elevation (m asl)
1	Luther Marsh	X				43°54'07"N	80°27'11"W	342
2	Homer Watson	X	X	X		43°24'18"N	80°26'14"W	318
3	Oakland Swamp	X				43°04'16"N	80°22'23"W	235
4	Guelph Lake		X			43°37'02"N	80°15'27"W	384
5	Indian Woods		X	X		43°22'53"N	80°21'91"W	310
6	Private White			X		43°24"44'N	80°13'02"W	307
7	Griffen West			X		43°16'17"N	80°21'07"W	314
8	Eramosa River				X	43°42'36"N	80°07'46"W	350

2.3 Methods

2.3.1 Tree-Ring Data

Increment cores were prepared following standard dendrochronological methods (Stokes & Smiley, 1968). Cores were glued into wooden mounts, polished on a belt sander and finally buffed by hand to reveal growth ring patterns. The annual ring widths were measured to 0.001mm using a WinDendro digital image processing and measuring system (Guay, Gagnon, & Morin, 1992), and were cross-dated using the statistical program, COFECHA (Holmes, 1983). Once trees from each site were successfully cross-dated (Appendix A), site master chronologies were created through the program ARTSAN (F. Cook & Holmes, 1984) by standardizing the individual cores in each chronology to form a group growth signal (Appendix B). By standardizing chronologies, variations in growth attributable to age, soil type and site history are dampened so as to allow better characterization of the climate-related growth signal. Each individual site chronology was detrended with a 50-year cubic smoothing spline with a 50% frequency response (E. R. Cook & Peters, 1981).

Individual master chronologies from each site were entered into a correlation matrix to determine the degree of statistical similarity between the sites for each species. Since all of the species-specific sites correlated to one another above critical levels and were statically significant ($P < 0.01$), cross-dated individual cores from the different sites were combined to create regional chronologies for each species (Table 2.2). As with the individual site master-chronologies, the regional master-chronologies were standardized through ARTSAN to create a unified growth signal (Fig. 2.3). These regional master-chronologies were used to establish species-specific growth-climate relationships with historical climate data.

Table 2.2 Correlation matrices of a 125-year time series (1882-2007) of radial-growth increments between species specific study sites in the Grand River Watershed

Eastern Hemlock				
Name	Luther Marsh	Homer Watson	Oakland Swamp	
Luther Marsh	X	0.313	0.254	
Homer Watson	0.313	X	0.26	
Oakland Swamp	0.254	0.26	X	
Sugar Maple				
Name	Guelph Lake	Indian Woods	Homer Watson	
Guelph Lake	X	0.63	0.431	
Indian Woods	0.63	X	0.4	
Homer Watson	0.431	0.4	X	
White Pine				
Name	Private White	Griffen West	Indian Woods	Homer Watson
Private White	X	0.484	0.437	0.421
Griffen West	0.484	X	0.655	0.531
Indian Woods	0.437	0.655	X	0.592
Homer Watson	0.421	0.531	0.592	X

Values of Pearson's *r* are listed. All values are significant to the 0.01 level. White spruce does not appear because it only occurred at one site.

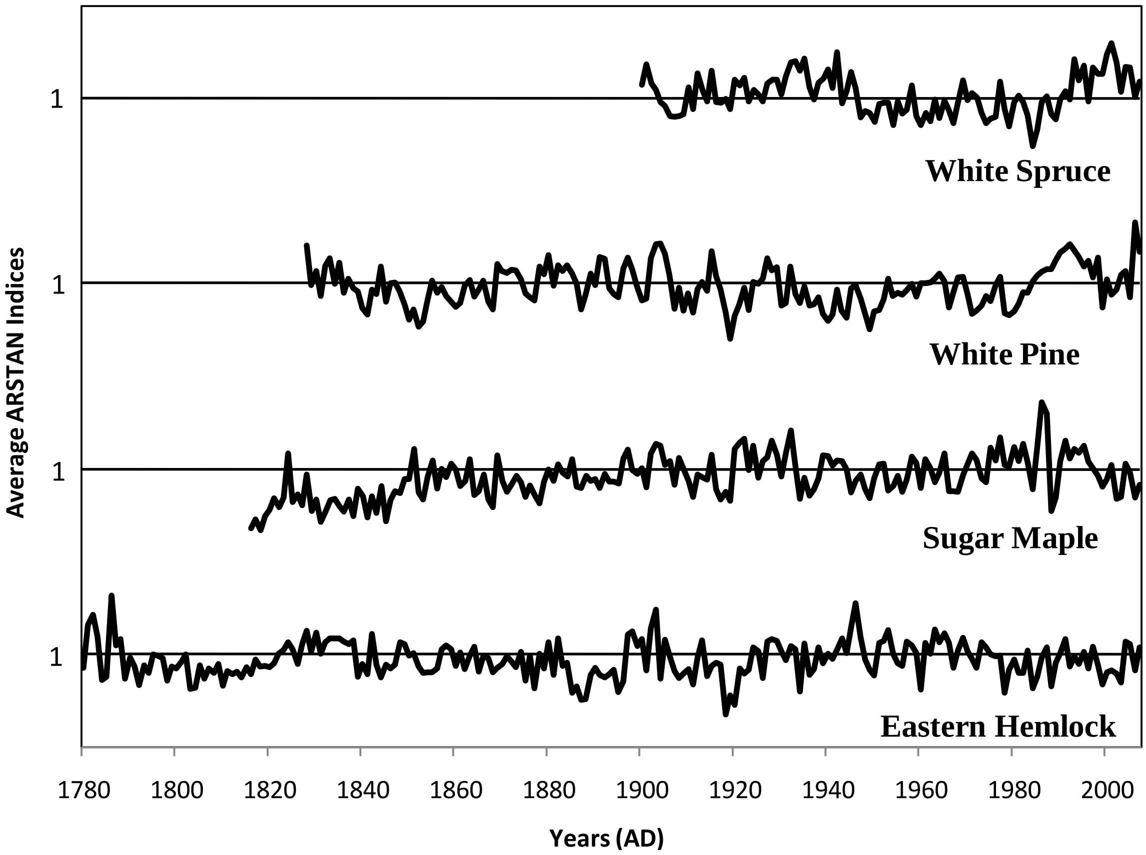


Figure 2.3 The standardized regional chronologies of the four study species in the Grand River Watershed

2.3.2 Past Climate Data

Species master-chronologies were entered into regression models to establish mathematical relationships between radial-growth and climate expressed as long-term monthly temperature and precipitation data from the Guelph OAC station (Environment Canada, 2008). Guelph OAC station was selected due to its central location relative to the sample sites. Missing data from the Guelph OAC station were filled using averages from four other nearby stations, namely Cambridge-Galt (43°19'47"N, 80°19'11"W, station identifier

#6141095), Woodstock (43°8'24"N, 80°46'11"W, station identifier #6149625), Fergus Shand Dam (43°43'47"N, 80°19'47"W, station identifier #6142400) and Stratford (43°22'48"N, 81°0'0"W, station identifier #6148100) (Fig. 2.2) (Environment Canada, 2008). Before using these substitutes, all the station data were analyzed to verify that their values were significantly correlated to one another. Less than 10% of the Guelph OAC station dataset needed to be filled using averages from the four other weather stations.

Temperature and precipitation variables from the previous year’s May until the end of the current year were compared to the standardized regional chronologies (Laroque & Smith, 2003). A tree’s current growth is often correlated with growth in the previous season and this factor has to be filtered out statistically. Thus, an independent variable was also added for one year’s previous growth for each species-specific model to account for the relationship between the current and previous year’s growth (Fritts, 1976).

Next, the climate and autocorrelation variables having the greatest impact on radial-growth were identified through a stepwise multiple regression analysis using SPSS (Version 16) (Table 2.3). The “F to enter” and “F to remove” confidence levels were set at 0.2 and 0.25, respectively, to limit the number of independent variables entered into the regression. The use of these limiting parameters approximated the “10%” rule of thumb recommended for such statistical tests, and ensured that ‘overfitting’ of the regressions did not occur (Laroque & Smith, 2003; Sokal & Rohlf, 1997). The predictive ability of these regression models was tested using a calibration/verification scheme. For all of the species, a 60/40 calibration to verification ratio was used. The calibration period for eastern hemlock,

Table 2.3 The study species' relationship with climate as determined by the stepwise regression analysis.

	Current year											
	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Mean Temp.												
Eastern Hemlock			+	-						+		
Sugar Maple					+							
White Spruce			+			-						
White Pine			+									
Precipitation												
Eastern Hemlock					+							
Sugar Maple							+					
White Spruce	+						+					
White Pine					+		+					

Previous year

	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Mean Temp.								
Eastern Hemlock			-					
Sugar Maple		-	-		-			
White Spruce			-					
White Pine		+	+					
Precipitation								
Eastern Hemlock			+					
Sugar Maple				+				
White Spruce								
White Pine							+	

The positive (+) and negative (-) significant growth relationships between the study species and climate as determined by the stepwise regression analysis white pine and sugar maple ran from 2006 to 1932 (n=74), and the verification period between 1931 and 1882 (n=49). Due to the limited number of mature white spruce samples, the calibration period for this species ran from 2006-1946 (n=60), and the verification period between 1945 and 1906 (n=39).

The growth-climate relationships illustrate that 66-84% of annual variance (r) in radial-growth for each of the four species can be explained using climate data from the filled Guelph OAC station dataset and one autocorrelation variable (Table 2.4). All of the models were significant when verified using standard goodness-of-fit tests (Table 2.5, Appendix C).

Table 2.4 Results of the stepwise regression analysis between annual radial-growth increments (dependant variable) and historical weather data from the Guelph OAC weather station

Dependent variable (model)	Number of independent variables in the equation	Explained r (r^2)
Master Eastern Hemlock	7	0.729 (0.53)
Master White Pine	7	0.84 (0.71)
Master White Spruce	6	0.762 (0.58)
Master Sugar Maple	7	0.667 (0.45)

All models include a 1-year lag parameter and are statically significant at $P < 0.01$.

Table 2.5 Pearson correlation values confirming the relationship between radial-growth and the calibration/verification periods for each of the species specific models, as well as the mean square error of prediction test (MSEP) illustrating the error between actual and modeled growth.

	Tree Species Models			
	Eastern Hemlock	Sugar Maple	White Spruce	White Pine
Calibration Period	0.729	0.667	0.761	0.84
Calibration MSEP	0.015	0.028	0.021	0.014
Calibration % error	12.71	16.82	15.03	12.6
Verification Period	0.495	0.23	0.323	0.617
Verification MSEP	0.053	0.044	0.049	0.034
Verification % error	25.04	21.61	21.94	19.15

2.3.3 Future Climate Data

CGCM3 model outputs were used to derive the future climate data through a 2.81° x 2.81° GCM grid square covering the latitudes 40°26'24” N to 43°15'00” N and longitudes from 81°33'36” W to 78°45'00” W (Fig. 2.1). CGCM3 provides climate projections for the period 1850-2100. In this instance, precipitation was summed as monthly totals and temperature data were reported as monthly means (Laroque & Smith, 2003). To test the capacity of CGCM3 to model the climate of the GRW, the model outputs were compared to the filled Guelph OAC weather station data for 1881-2000. A visual comparison of the actual to modeled climate data shows that CGCM3 produced average temperature predictions about 0.7°C cooler than those recorded at Guelph OAC station (Fig. 2.4). On the other hand, the modeled precipitation values appear very similar to the recorded data, with only a few exceptions evident in the older sections of the dataset (Fig. 2.5). It is important to note that CGCM3 produces 21st-century temperature projections for Ontario that are in line with other

GCMs, while it generates precipitation data that is generally wetter than comparable models (Pacific Climate Impacts Consortium (PCIC), 2007).

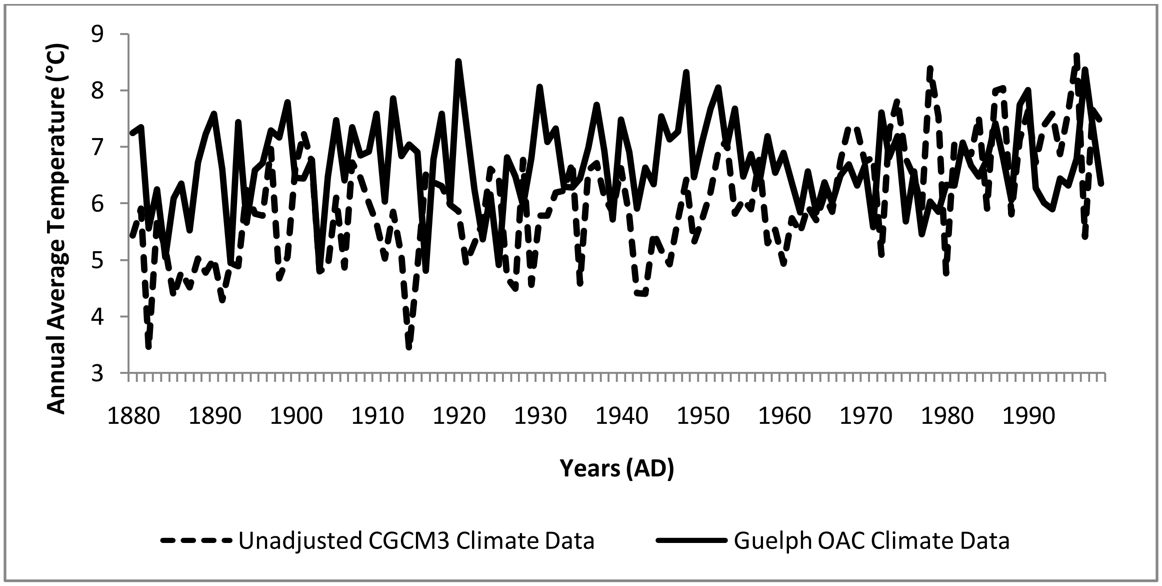


Figure 2.4 A comparison of temperature data from Guelph OAC station (1881-2000) and the unadjusted CGCM3 data derived from the surrounding grid square.

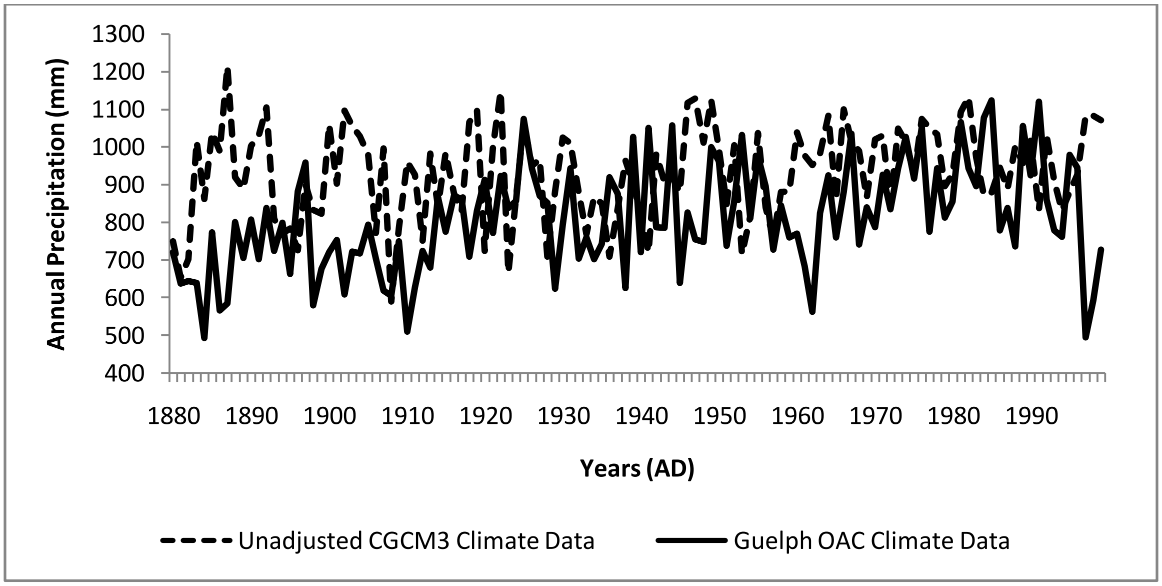


Figure 2.5 A comparison of precipitation data from Guelph OAC station (1881-2000) and the unadjusted CGCM3 data derived from the surrounding grid square.

Divergence between the CGCM3 and Guelph OAC climate data were unsurprising, as the CGM grid square used for this project covered a large area relative to the study site, and as the center of the gird square falls south of the Guelph OAC weather station. To account for these issues, the climate model data were adjusted to represent the study area more accurately. The conversion began by subtracting the CGCM3 data from the Guelph OAC data on a monthly scale for each year during 1881-2000. These results were averaged for each month to create monthly divergence values. These values were then applied back onto the annual CGCM3 figures at the same monthly resolution. The outcome of this correction was a CGCM3 past climate dataset that better matched the historical Guelph OAC records (Fig. 2.6 and Fig. 2.7). This change factor was later applied to the future dataset, which tailored the zonal CGCM3 data to the climatic conditions experienced in Guelph.

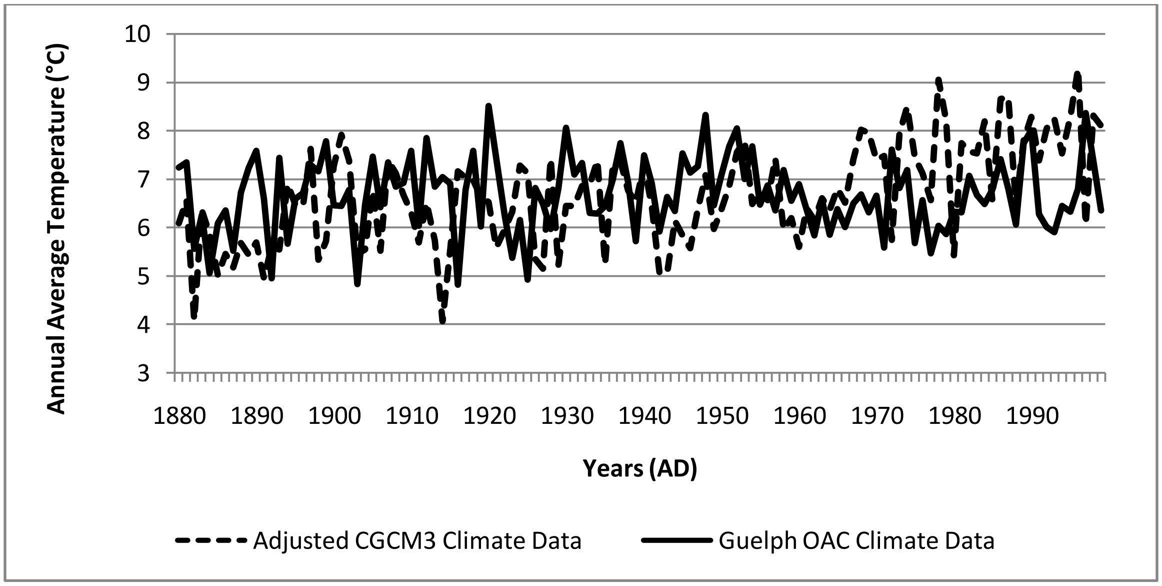


Figure 2.6 A comparison of temperature data from Guelph OAC station (1881-2000) and the adjusted CGCM3 data derived from the surrounding grid square.

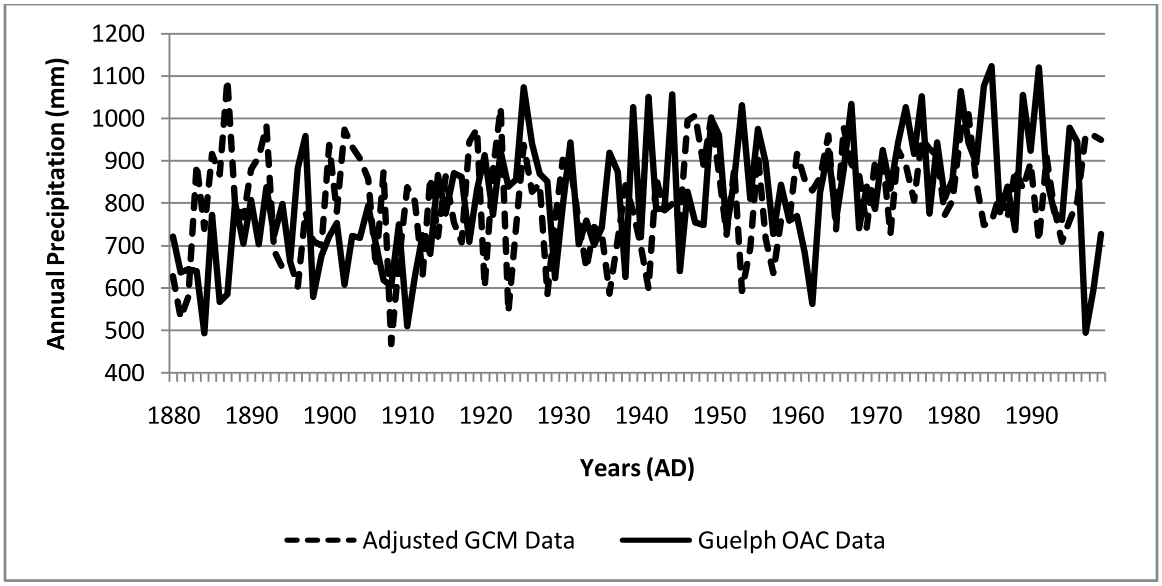


Figure 2.7 A comparison of precipitation data from Guelph OAC station (1881-2000) and the adjusted CGCM3 data derived from the surrounding grid square.

2.3.4 Forecasting Radial-Growth

The growth-climate relationships established through the stepwise regression analysis were applied to the adjusted CGCM3 future dataset (2000-2100) to forecast the radial-growth patterns for each species. Forecasts were produced based on low (B1) to moderate (A1B) SRES emissions scenarios. Under these scenarios, mean temperatures in the GRW are expected to warm by approximately 2.5°C (B1) to 3.0°C (A1B) by 2100, while annual precipitation rates are expected to increase by about 50mm (B1) to 150mm (A1B) by century’s end (Fig. 2.8 and Fig. 2.9).

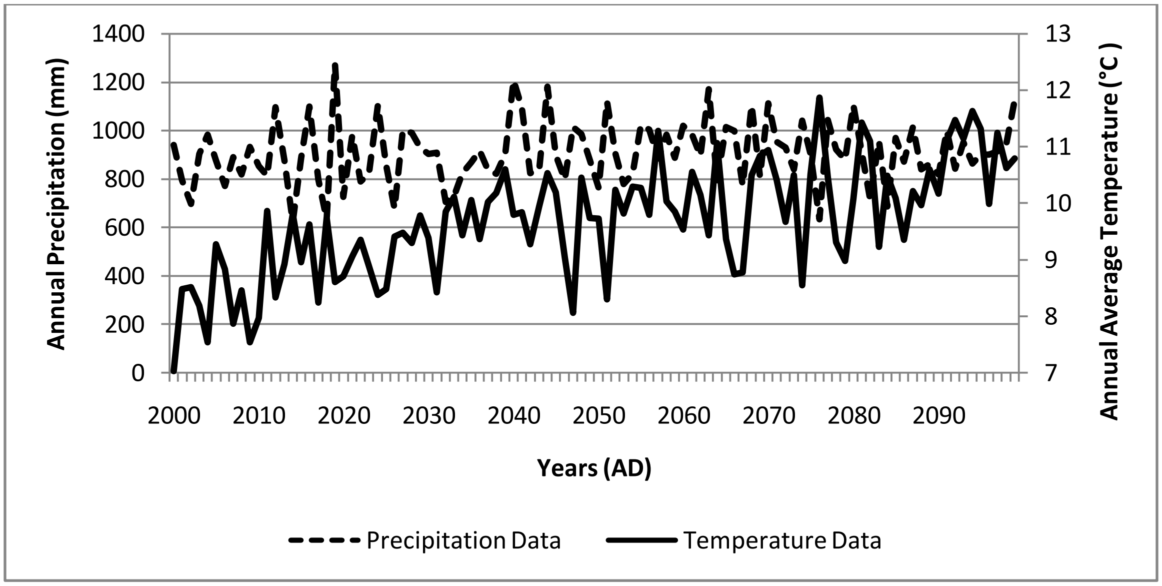


Figure 2.8 Predicted temperature and precipitation trends for the study site under the B1 (550 CO_2 ppm) emissions scenario.

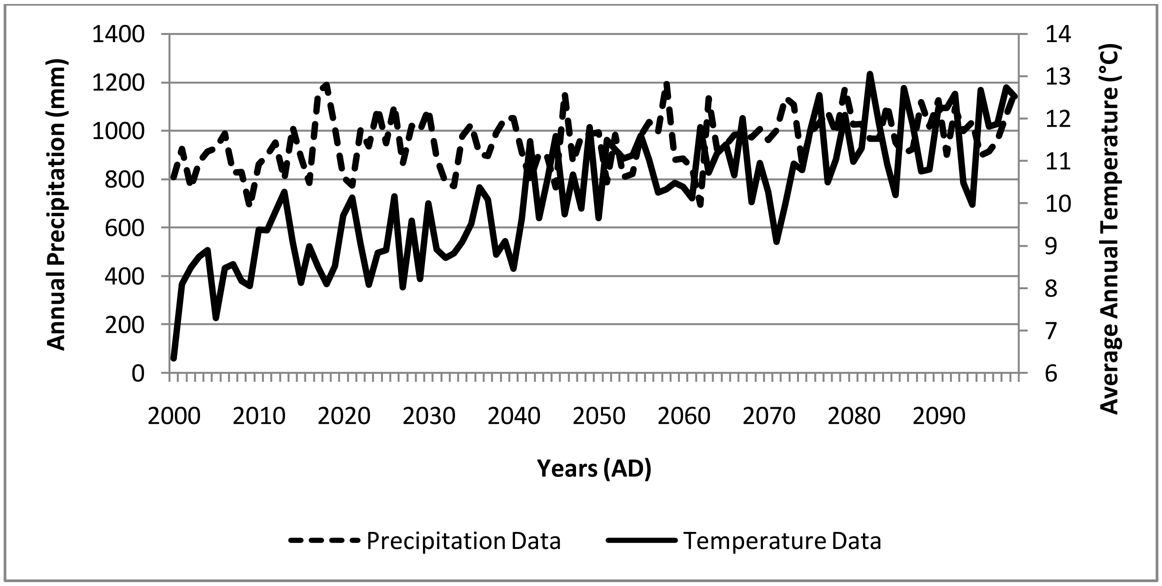


Figure 2.9 Predicted temperature and precipitation trends for the study site under the A1B (720 CO_2 ppm) emissions scenario.

2.4 Results

2.4.1 Eastern Hemlock

The radial-growth response of eastern hemlock in the GRW to past (1881-2006) and future climates (2007-2100) is shown in figures 2.10 and 2.11. Under the B1 emissions scenario, the radial-growth rates of eastern hemlock remain within its long-term range of variation throughout the 21st-century (Fig. 2.10). The forecast shows slightly below average growth for eastern hemlock through the 2060s, followed by a recovery to historical averages for the rest of the century. Under the A1B scenario, eastern hemlock displays slightly above average radial growth patterns until 2090 when rates drop sharply below historical averages (Fig. 2.11). The general stability of eastern hemlock throughout the next century can be attributed to the significant positive and negative climatic factors that influence radial-growth essentially negating one another. In particular, eastern hemlock's positive growth response to March temperature counteracts the unfavorable growth effects of warmer and drier Julys.

2.4.2 Sugar Maple

Under the B1 scenario, radial-growth rates for sugar maple drop below the smallest recorded annual growth increments by 2020 (Fig. 2.12). Following that period, growth rates stabilize until 2100 at about 50% of historical averages. This eventual stabilization is not evident, however, under the A1B scenario, in which sugar maple growth increments consistently decline throughout the 21st-Century (Fig. 2.13). This second forecast illustrates sugar maple exceeding the smallest historical growth rates by 2030, and only generating rings about 25% as wide as the historical average by century's end. The decline of sugar maple in the GRW is due to the warmer and drier summers anticipated by CGCM3 under both emissions scenarios.

2.4.3 White Spruce

White spruce will experience rapidly declining growth rates in the B1 forecast, resulting in ring widths smaller than the historical average by 2030 (Fig. 2.14). After this initial drop, annual growth stabilizes for the next seven decades at about 50% of past averages. Under the higher emissions scenario, growth rates for white spruce will steadily decline throughout the century (Fig. 2.15). Consistently decreasing radial-growth rates in white spruce are primarily linked to hot and dry summers.

2.4.4 White Pine

In contrast to white spruce, white pine will experience rapid increases in radial-growth rates through the next century under both emissions scenarios. The B1 forecast shows white pine radial-growth increments quickly rising until the 2060s at which point they stabilize at growth rates around 3 times the historical average (Fig. 2.16). The A1B forecast shows a constant increase in radial-growth until 2100 when growth rates reach levels almost 4 times greater than the historical average (Fig. 2.17). The magnitudes of these white pine forecasts are exaggerated because of the species' strong association with the previous growth (PG) variable. This variable, which explains 78% of variance in the forecasted curve, makes the forecasts rise almost exponentially, as the high autocorrelation value appears to create a compounding positive feedback loop. Removal of the PG variable from the white pine model leads to the same increasing growth trend, but at a lower trajectory (Fig. 2.18 and Fig. 2.19).

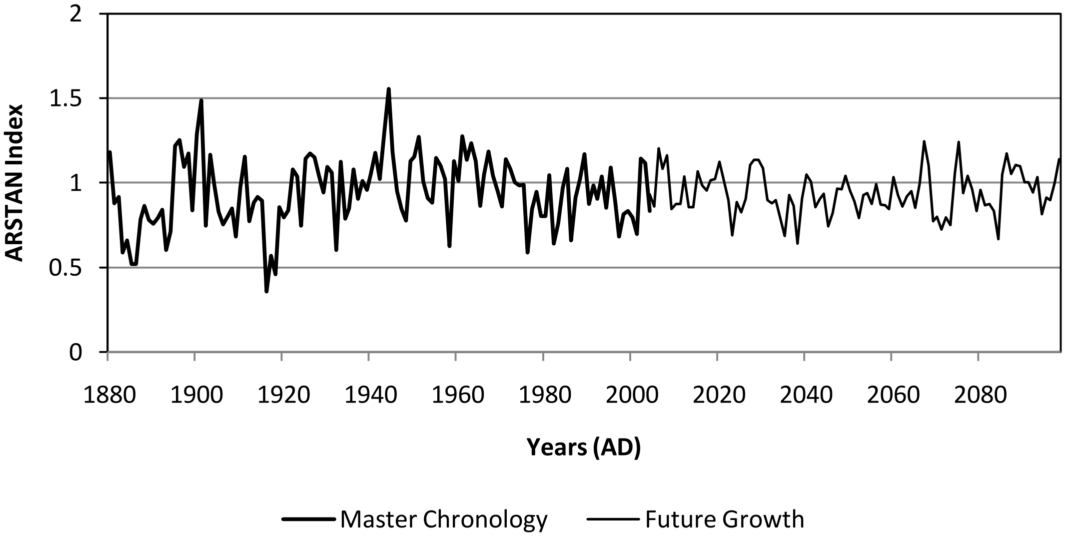


Figure 2.10 Eastern hemlock radial-growth forecast, B1 emissions scenario

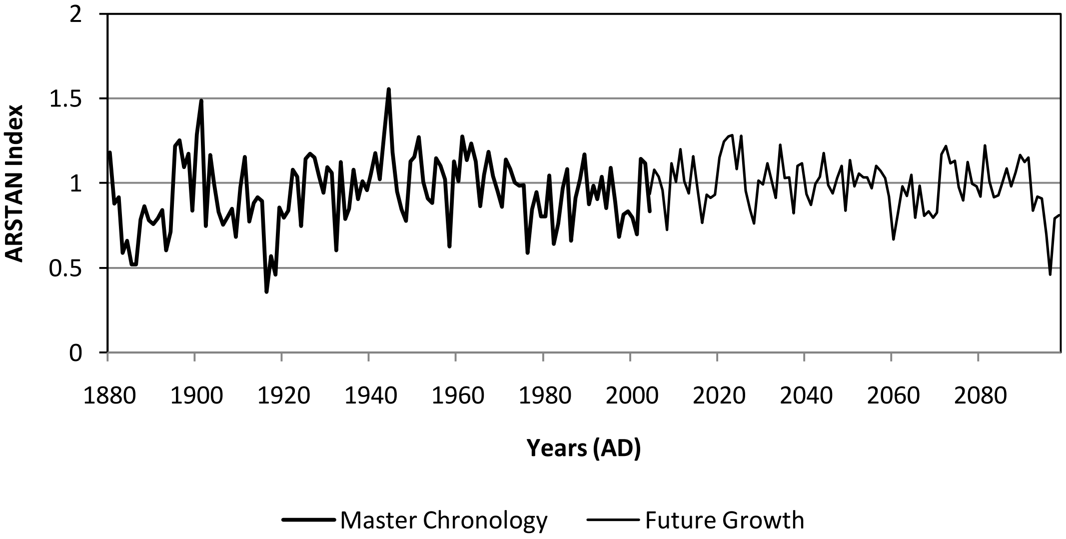


Figure 2.11 Eastern hemlock radial-growth forecast, A1B emissions scenario

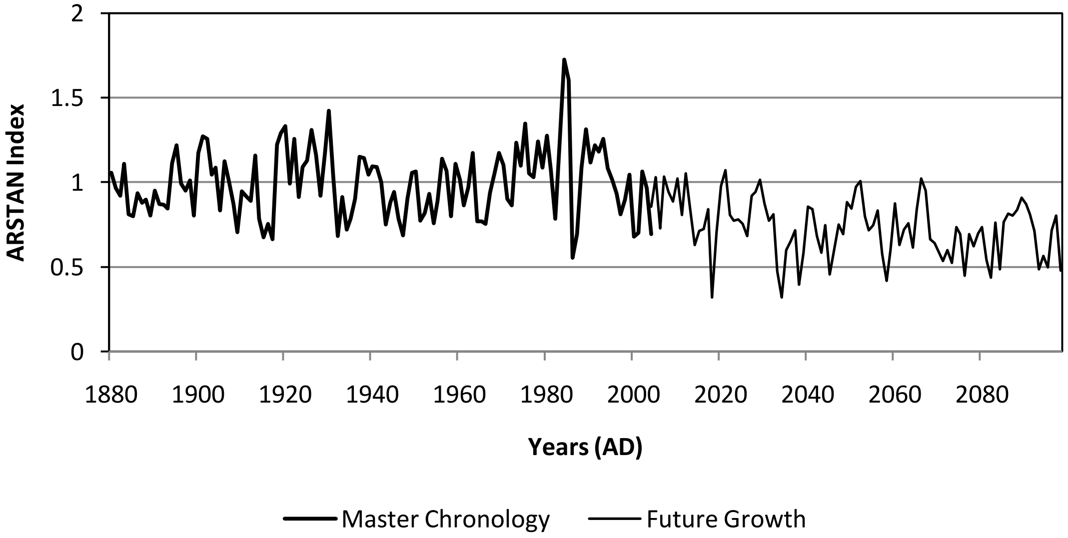


Figure 2.12 Sugar maple radial-growth forecast, B1 emissions scenario

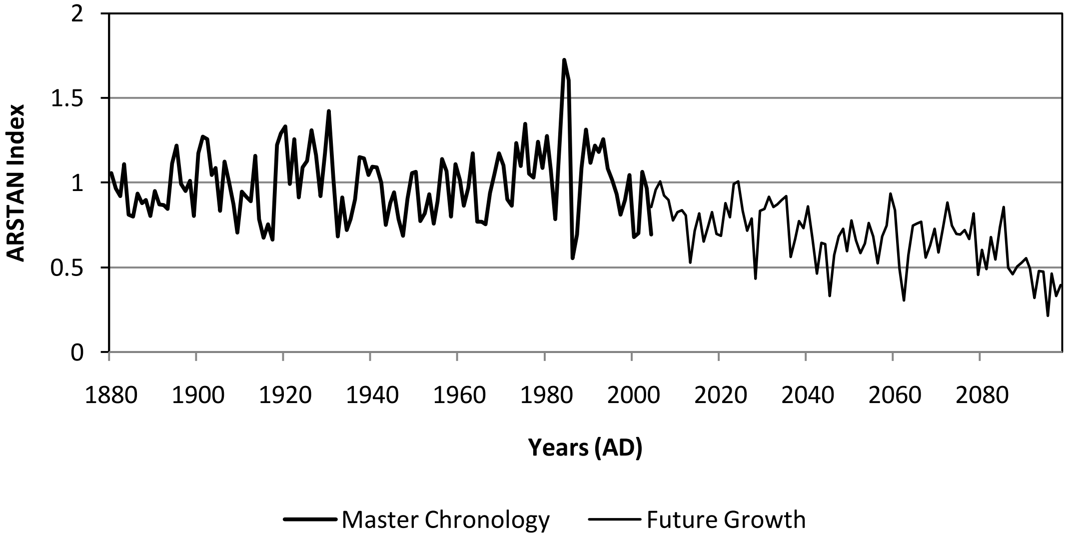


Figure 2.13 Sugar maple radial-growth forecast, A1B emissions scenario

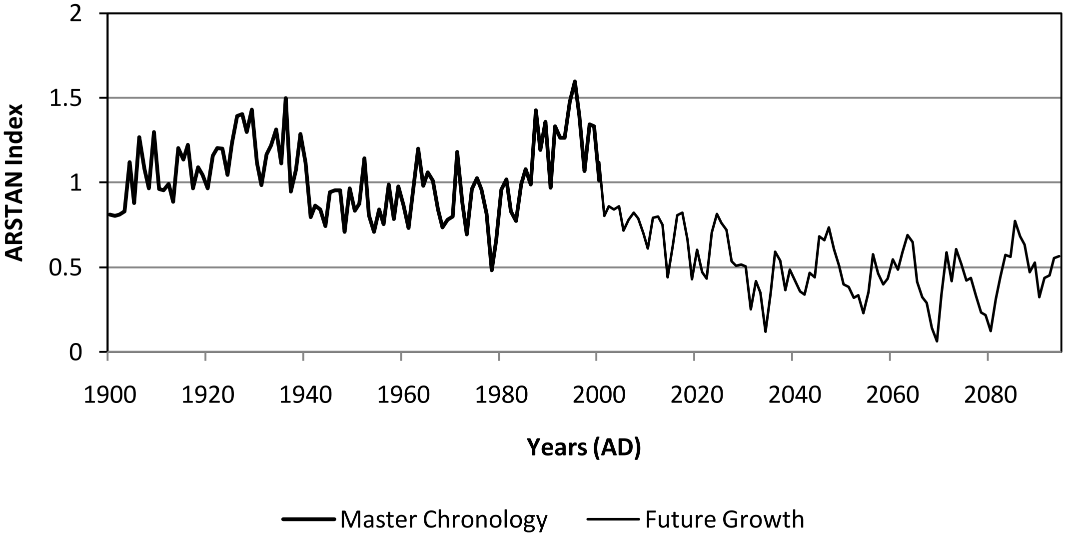


Figure 2.14 White spruce radial-growth forecast, B1 emissions scenario

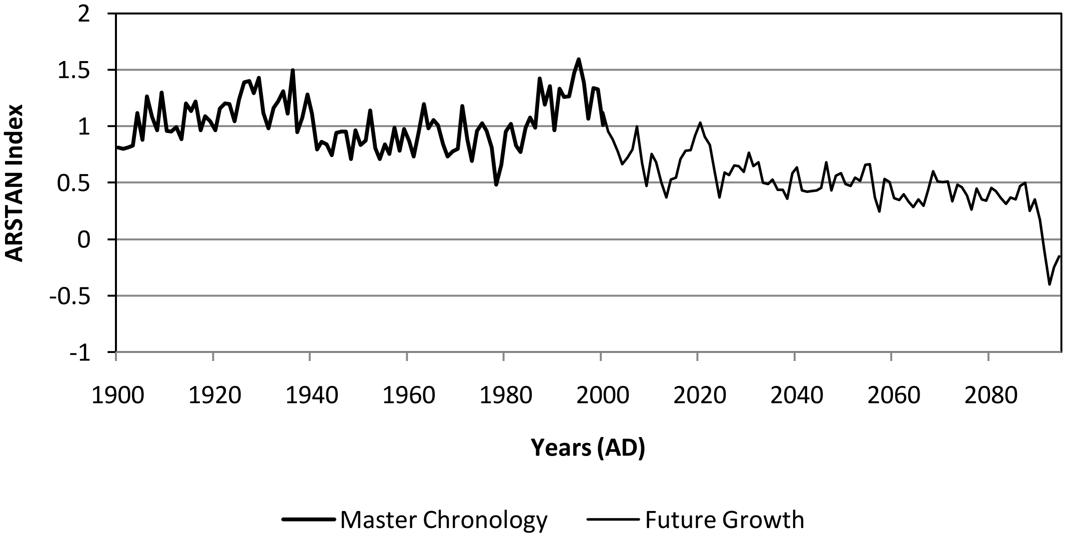


Figure 2.15 White spruce radial-growth forecast, A1B emissions scenario

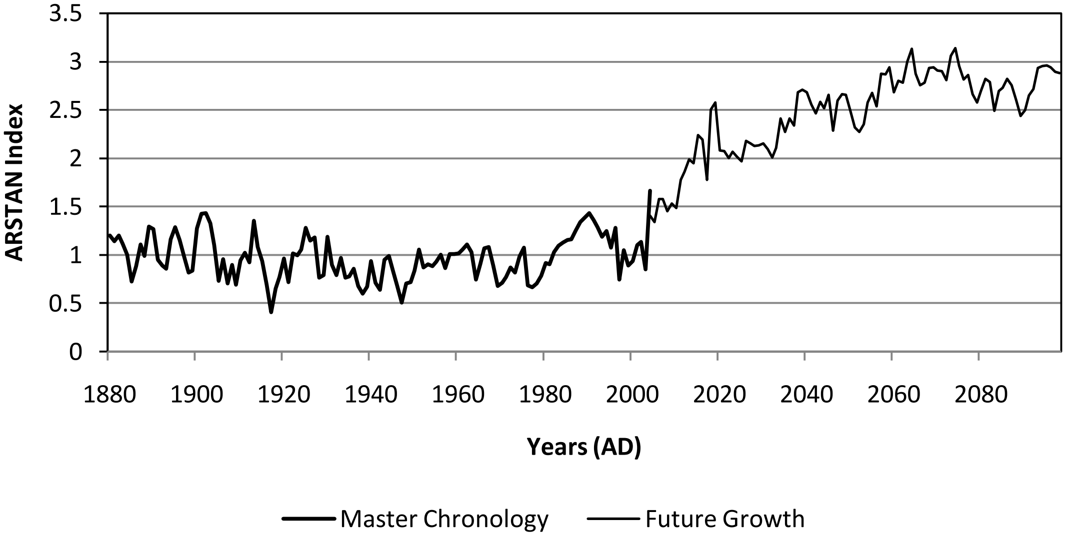


Figure 2.16 White pine radial-growth forecast, B1 emissions scenario

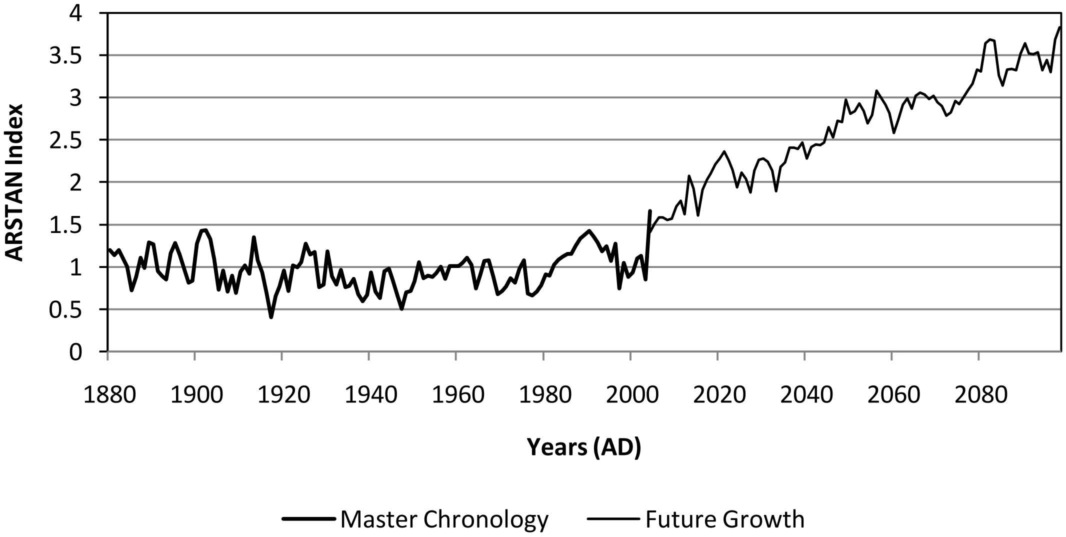


Figure 2.17 White pine radial-growth forecast, A1B emissions scenario

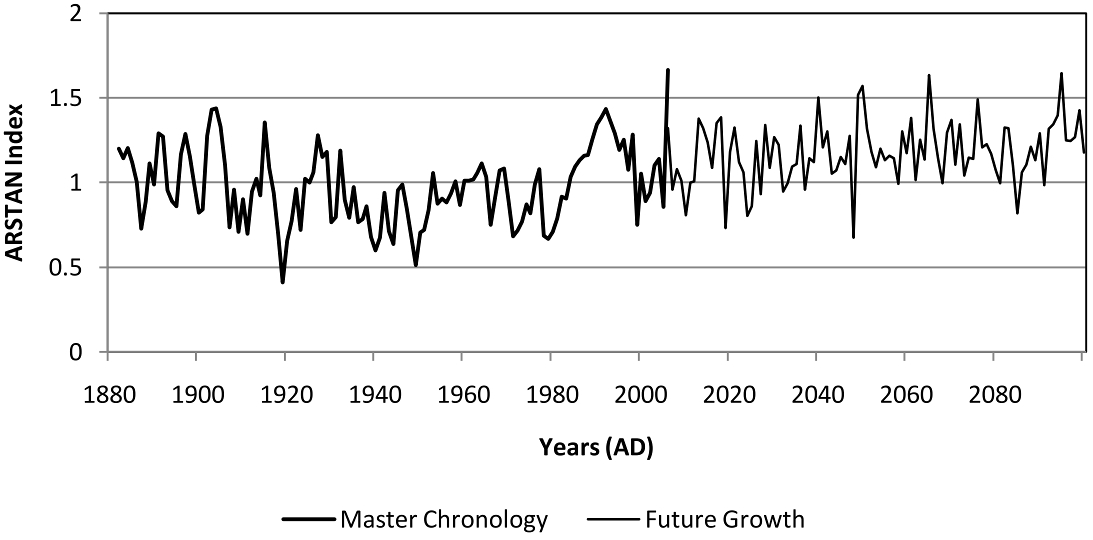


Figure 2.18 White pine radial-growth forecast, B1 emissions scenario, excluding previous growth variable

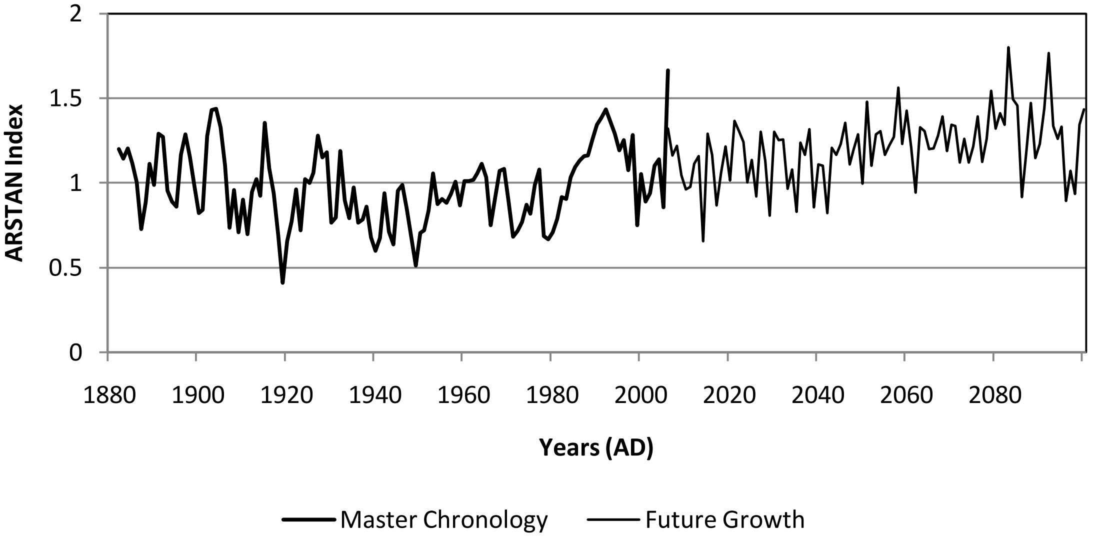


Figure 2.19 White pine radial-growth forecast, A1B emissions scenario, excluding previous growth variable

2.5 Discussion

2.5.1 Eastern Hemlock

The stability of eastern hemlock throughout the 21st-century can be attributed to its strong positive growth relationships with March temperature and July precipitation in the year prior to ring formation, as well as its negative growth reaction to previous July temperature. The projected warming trend in March (3.5-4°C) essentially offsets the anticipated warmer and drier Julys. The notion that increasing March temperatures could potentially negate the effects of drier summers on the growth rates of eastern hemlock was initially suggested by Cook and Cole (1991) in their dendroclimatic study of the species throughout most of its range. Another factor in eastern hemlock's steady forecast could be its positive growth relationship with October temperature and negative association with April temperature, both of which are expected to rise through the next century. The only other climatic factor used in the eastern hemlock model was its positive growth link to May precipitation, which is projected to remain constant until 2100 under both emissions scenarios.

The strong positive relationship between eastern hemlock growth and March temperature evident in this study supports related findings (Abrams, van de Gevel, Dobson, & Copenheaver, 2000; Black & Abrams, 2005; E.R. Cook & Cole, 1991; J. Tardif, Brisson, & Bergeron, 2001). The hypothesis that higher March temperatures result in greater hemlock growth through the quicker removal of snow cover and earlier than normal resumption of photosynthesis is further supported by this paper (E.R. Cook & Cole, 1991; J. Tardif et al., 2001). Also, the limitation of eastern hemlock growth by July drought in the year prior to ring formation is supported by literature examining the species' growth-climate relationship during the last century (Abrams et al., 2000; E.R. Cook & Jacoby, 1977; Gove & Fairweather, 1987; Lyon, 1935; J. C. Tardif, Conciatoril, Nantel, & Gagnon, 2006), as well as its decreased pollen occurrence during the mid-Holocene (Calcote, 2003; Foster, Oswald, Faison, Doughty, & Hansen, 2006; Shuman et al., 2001). Other climatic factors affecting the growth of eastern hemlock in the GRW (+ October temperature, + May precipitation, -April temperature) do not appear to have been previously noted in the literature. Connections can be drawn, however, between this study and that of Tardif, Brisson, and Bergeron (2001), who found that eastern hemlock growth responds positively to June precipitation and negatively to May temperature. Combined with this study, these results suggest that late spring/early summer water balance is important to the radial-growth of eastern hemlock, especially in May.

2.5.2 Sugar Maple

The downward trajectory of the sugar maple forecasts is due to historical growth-climate relationships that show the species reacting negatively to warm June, July and August temperatures in the year prior to ring formation, as well as its positive growth response to precipitation in August of the previous year and July of the current year. Since both climate change scenarios project warmer and drier summers, it is not surprising that sugar maple will decline in the region when considering climatic factors alone. These results, which suggest sugar maple is limited by summertime drought, align with other published findings (Bauce & Allen, 1991; Bernier & Brazeau, 1988; Friesner & Friesner, 1942; Graumlich, 1993; Hartmann & Messier, 2008; Hornbeck, Smith, & Federer, 1988; Miller, 1951; Ni & Pallardy, 1992; Payette, Fortin, & Morneau, 1996; Sinclair, 1964; St. Clair, Sharpe, & Lynch, 2008; J. Tardif et al., 2001; Yin, Foster, Morrison, & Arp, 1994). The positive link between sugar maple growth and May temperature has also been noted (Graumlich, 1993; Lane, Reed, Mroz, & Liechty, 1993; J. Tardif et al., 2001). The modeled rise in May temperatures by 2-4°C, however, will do little to counter the detrimental effects of an increasingly arid late growing season on sugar maple growth within the GRW.

2.5.3 White Spruce

The forecast decline of white spruce radial-growth is largely due to its strong negative growth association with previous July and current June temperature, as well as its positive link to July precipitation. While white spruce growth also displays a positive connection to March temperature, warmer springs will not offset the drier growing season anticipated for the GRW. The limitation of white spruce by previous year and current summertime temperatures has been well documented, as has its positive association with July precipitation (Barber, Juday, & Finney, 2000; Chhin & Wang, 2002, 2008; Chhin, Wang, & Tardif, 2004; Girardin & Tardif, 2005; Hogg & Wein, 2005; Larsen & MacDonald, 1995; St. George, Meko, & Evans, 2008; J. Tardif & Conciatori, 2001; Wilmking, Juday, Barber, & Zald, 2004). The results of this study are in line with others that suggested the range of white spruce, particularly at its southern limit, is controlled mainly by moisture stress caused directly by low precipitation levels, or indirectly by temperature-induced drought stress (Chhin & Wang, 2002, 2008; Chhin et al., 2004; Hogg & Hurdle, 1995; Zoltai, 1975). Furthermore, the historical growth-climate relationships revealed in this study support paleoclimatic data from New England and elsewhere that showed a dramatic decline in *Picea* as temperatures increased during the Holocene (Hou et al., 2006; Huang, Shuman, Wang, & Webb III, 2002; Stuiver, Grootes, & Braziunas, 1995), as well as its reemergence over the past 2000 years in response to cooler and moister conditions (Davis, Spear, & Shane, 1980; Foster & Zebryk, 1993; Schauffler & Jacobson Jr., 2002; Shuman, Newby, Huang, & Webb, 2004).

As in eastern hemlock, the positive growth response of white spruce to March temperature is likely due to the earlier onset of snowmelt. This relationship has been noted by other researchers studying white spruce throughout its range (Driscoll, Wiles, D'Arrigo, & Wilmking, 2005; J. Tardif & Conciatori, 2001; Wilmking et al., 2004). The final climatic factor included in the white spruce forecast was its weak positive growth association with January precipitation. While January temperature has been identified as important to the growth of white spruce before (Chhin & Wang, 2008), it appears that the species' growth relationship to January precipitation has not been noted previously. Perhaps more snow in January prevents the destructive effects of soil freeze by providing an insulating effect, or it benefits white spruce in spring by providing extra moisture.

2.5.4 White Pine

The increasing radial-growth predicted for white pine in the GRW is due to the species' positive growth association with temperature in June and July of the year prior to ring formation as well as with March of the current year. Also, white pine's positive growth relationship with precipitation in November of the previous year and May of the current year result in high future growth driven by these variables, as precipitation is expected to slightly increase in the GRW during both months under the two emissions scenarios. The only other climatic factor included in the radial-growth forecasts was white pine’s positive growth association with July precipitation, which is expected to decrease very slightly (5-10mm) according to the modeled climate. Given the negligible increases expected for November and May precipitation in this century, in addition to the minimal decreases expected for rainfall in July, monthly precipitation appears relatively unimportant for the growth of white pine in the GRW. Temperature as the primary factor driving the growth of white pine was also noted by Graumlich (1993).

Given the wide ecological amplitude of white pine and its propensity to occupy several physiographic regions (Wendel & Smith, 1990), it is unsurprising that ambiguous and contradictory findings appear when reviewing its growth response to climate. For instance, some studies have shown that white pine thrives in damper and cooler climates (Abrams et al., 2000; Denton & Barnes, 1987; Hotchkiss, Calcote, & Lynch, 2007), while other research supports the findings of this thesis. The positive growth relationship between white pine and March temperature in the GRW, for example, is consistent with other papers displaying the species’ sensitivity to warmer temperatures during the early growing season (March/April) (Graumlich, 1993; Kilgore & Telewski, 2004; Mácová, 2008). Like other conifers, the positive growth response of white pine to March temperature is likely due to the ability of its evergreen foliage to take advantage of early growing season warmth (Fritts, 1976). The positive connection between the growth of white pine and a warmer, drier mid-growing season is also supported in the literature, particularly in articles discussing the expanding range of the species throughout eastern North America during the Holocene (Jacobson Jr. & Dieffenbacher-Krall, 1995; Newby et al., 2000).

The positive association between the growth of white pine and July precipitation in the GRW also supports previously published works. For example, Denton (1987) found that white pine in Michigan had a moderately high-ratio of July-August evapotranspiration to precipitation rate, and Mácová (2008) noted the species' positive growth response to summer rain in dry areas. Conversely, the influence of previous November and current May precipitation on the radial-growth of white pine as highlighted in this study has not been mentioned before.

The prospective success of white pine in the GRW is in line with Jacobson and Dieffenbacher-Krall (1995), who suggested that future warming could favor the next generation of white pine trees and be well-tolerated by existing stands. Importantly, the magnitudes of the white pine forecasts presented here are exaggerated because of the species' strong association with the previous growth variable. Until further research is conducted on the effects of this variable in the establishment of historical growth-climate relationships, in addition to its theoretical and statistical role in dendroclimatological modeling, conclusions surrounding radial-growth forecasts should only be drawn based on the general trajectory of the results, as opposed to the specific rates of projected growth (Phillips, 2009). This is particularly important when examining species with high autocorrelation rates, such as in this white pine case.

2.5.5 Predictive Limitations of Radial-Growth Forecasting

The radial-growth forecasts are predominately limited by the accuracy of the CGCM3 future climate dataset. CGCM3 and related models are constantly being updated and refined with more, and better, spatially continuous data. With future climate scenarios and new generations of models, the radial-growth forecasts upon which they are based also need updating. This is particularly true in the GRW given the complex effects of the Great Lakes on climate (Burnett, Kirby, Mullins, & Patterson, 2003). Second, the radial-growth models presented here were calibrated using only the past 60-74 years of climate data. While there has been much variability during this time, there are future forecasted maximums of both temperature and precipitation that fall outside the range of the past 60-74 years. Thus, the models are limited in their capacity to extrapolate radial-growth under forecasted climates which exceed past climatic ranges. Finally, these models did not account for a host of other climatic and non-climatic variables that would surely impact the four species. For example, the response of the study species to elevated CO_2 and other types of air pollution were not considered (Bartholomay, Eckert, & Smith, 1997; Bazzaz, Coleman, & Morse, 1990), nor did the model account for the shifting climatic factors that the species may depend on at various stages during their life cycle (Colenutt & Luckman, 1991; Parish, Antos, & Hebda, 1999; Szeicz & MacDonald, 1994). Also, the potential effects of pathogens, insects and competition in the GRW were not incorporated, and no attempt was made to predict the propensity of the study species to successfully disperse or germinate under changing climatic scenarios.

2.6 Conclusion

Radial-growth forecasting models have been developed for four significant tree species in the Grand River Watershed. Regional master dendrochronologies for each of the study species were built, standardized, and used to establish growth-climate relationships. Using 21st-century modeled climate scenarios from CGCM3, these historical growth-climate relationships were extended to 2100 to forecast the radial-growth rates for each of the species. Results indicate that eastern hemlock radial-growth will remain stable throughout the next century, sugar maple and white spruce growth will start to decline, and white pine growth will increase. While the magnitudes of the forecasts were amplified by the presence of the previous growth variable, they are based on historical growth-climate relationships that are statically significant and strongly supported in the literature. Despite inherent limitations, this modeling technique successfully used future climate scenarios to predict radial-growth rates, instead of simply relying on past trends and making casual inferences about the future. Given the results of this study and the others upon which it was based, the usefulness of radial-growth forecasting as an effective climate change adaptation tool is evident.

CHAPTER 3: Radial-Growth Forecasting as a Planning and Management Tool in the Grand River Watershed of Ontario, Canada

3.1 Introduction

Rapidly warming temperatures, in conjunction with highly fragmented landscapes, threaten the health of forests throughout North America. Consequently, government officials and academics have recommended adaptation strategies (Office of the Auditor General, 2006; Parry et al., 1998; Scott & Lemieux, 2007). Such measures typically focus on the future success of individual trees species. Therefore, many scientists have worked to predict the future ranges, habitats and growth rates of individual species given likely climate change scenarios. Much of the latest work has been based on course models, particularly those predicting continental-scale range shifts and habitats using the Climate Envelope (CE) approach (Iverson & Prasad, 1998; Iverson, Prasad, Matthews, & Peters, 2008; McKenney et al., 2007; Walker, Davis, & Sugita, 2002). While these large-scale models are useful for examining the magnitudes of potential changes, they are often conducted at scales beyond the scope of most managers and planners, and fail to account for the local genetic adaptations of forest trees to climate (Laroque, 2005; Morgenstern, 1996; Pilkey & Pilkey-Jarvis, 2007). As a result, recent literature has favored finer-scale forestry models (Heller & Zavaleta, 2009; Millar et al., 2007; Pilkey & Pilkey-Jarvis, 2007; Scott et al., 2002; Suffling & Scott, 2002).

To predict the success or demise of individual tree species at more relevant and useful scales (i.e. watershed and sub-watershed), researchers have begun forecasting the radial-growth rates of socially, economically, ecologically and environmentally significant tree species using dendroclimatology. Laroque and Smith (2003) were the first to model radial-growth patterns in their study of five high-elevation conifers on Vancouver Island, Canada. To do so, the authors initially constructed species-specific relationships between radial-growth and past climate data. Next, they extended these growth-climate relationships to 2100 using modeled climate data to project the future radial-growth rates for each of their study species. As a result, the authors identified which species would experience higher or lower radial-growth rates under probable climate change scenarios. This knowledge is important, as trees facing climatic stress are more likely to succumb to competition, disease or insect attack (van Mantgem et al., 2009).

Despite the significance and success of Laroque and Smith's (2003) study, only Girardin, Raulier, Bernier, and Tardif (2008) have replicated their methods in a study of three species within the Duck Mountain Provincial Park of Manitoba, Canada. Furthermore, no researcher has explained how radial-growth forecasts could be used in the formulation of effective environmental planning policy or forest management strategy. Thus, this paper uses the results of a recently completed radial-growth forecast to show the study's implications for regional planning and management. The paper begins by reviewing evidence of past and future climate change, the subsequent calls for climate change adaptation strategies, and the effects of warming temperatures and land use patterns on trees. Next, examples of course and fine scale forestry models are presented to display the advantages of the latter when planning for forests in a rapidly changing climate. Finally, the results of a radial-growth forecasting study from the Grand River Watershed (GRW) of Ontario, Canada are presented, and suggestions regarding how this study could influence environmental planning policy and forest management strategy in the region are raised.

3.2 Evidence of Climate Change

The Intergovernmental Panel on Climate Change (IPCC) recently reported strong evidence of a pending and profound change in global climate due to anthropogenic activities (2007a). Globally, the IPCC (2007a) estimated that mean temperatures have increased by 0.74°C over the past 100 years, and will probably rise an additional 1.8 to 4°C by the end of the 21st-century depending on future greenhouse gas emissions scenarios. Hanson et al. (2001) argued that these estimated rates of warming have been unprecedented in the last 10,000 years, and that current average global temperatures are within 1°C of the maximum temperature of the past million years. Thus by 2100, average global temperatures could be higher than any other time during the Quaternary Period.

The IPCC (2007a) projected that future climate change will generally affect land areas and high latitudes more than the oceans and tropics. For example, Canada is projected to experience substantially higher rates of warming than the global average, with mean annual temperature increases between 3.1 and 10.6 °C before the end of the century (Pacific Climate Impacts Consortium (PCIC), 2007; Scott & Lemieux, 2007). These rapid increases in temperature are expected to significantly alter natural systems and feedback-loops such as the hydrologic cycle (Trenberth, Dai, Rasmussen, & Parsons, 2003), as well as geographic ranges of numerous plant and animal species (Higgins & Harte, 2007; Intergovernmental Panel on Climate Change (IPCC), 2007b; Iverson et al., 1996; Schwartz et al., 2001).

3.3 Calls for Climate Change Adaptation Strategies

Current and projected climate change effects have led numerous North American researchers and government officials to recommend adaptation strategies. For instance, the *Report of the Commissioner of the Environment and Sustainable Development* (Office of the Auditor General, 2006) recently proposed that all levels of government begin to develop comprehensive action plans that deal with climate change adaptation, and that new ways to connect related researchers to decision makers be implemented. The report warns that failure to invest in climate change research will affect Canada’s ability to make wise decisions. Likewise, Scott and Lemieux (2007, p.348) suggested that Canada’s “protected areas will need to be established, planned and managed differently if they are to meet the conservation challenges posed by climate change over the 21st century and beyond.” Finally, Parry, Hulme, Nicholls and Livermore (1998) warned that future climate change could be very serious for society and hazardous for nature if progressive plans, policies and strategies are not put forth.

3.4 Climate Change and Land-Use Effects on Trees

Plant species have responded to past climate changes through range shifts and alterations in the timing of key-life events, notably budburst and seasonal migration patterns (Higgins & Harte, 2007; Parmesan & Yohe, 2003; Root et al., 2003). Paleoecological evidence has documented such responses following the end of the last glaciation about 10,000 years ago (Delcourt & Delcourt, 1988; Liu, 1990; Malanson, 1993; J. W. Williams, Shuman, Webb, Bartlein, & Leduc, 2004). Similarly, recent warming trends have affected plant species. A study by Parmesan and Yohe (2003) concluded with “very high confidence” that the trend of increasing temperatures during the 20th-century significantly altered the ranges and physiological timing for 279 of the plant species they studied worldwide. Furthermore, Soja et al. (2007) recently highlighted the uphill migration of white spruce tree-lines in mountainous Alaska, while others have noted longer growing seasons in Europe of up to 20 days since the 1960s (Linderholm, 2006; Menzel, 2000; Walther & Linderholm, 2006). Since 21st-century climate changes are projected to far exceed those of the 20th-century, marked transformations in ecosystem functions, species interactions, population biology and the distribution of plants are expected (Chapin et al., 2004; Melillo et al., 1990; Schwartz et al., 2001).

Even under conservative greenhouse gas emissions scenarios, the large and rapid climate changes expected throughout the 21st-century imply species migration at rates about ten times faster than those supposed for the last postglacial period (J. A. Malcolm et al., 2002; Scott & Lemieux, 2007; Solomon & Kirilenko, 1997). Consequently, researchers have argued that the migrations of trees will lag behind the poleward shifts of their climatic zones (Gear & Huntley, 1991; Intergovernmental Panel on Climate Change (IPCC), 2007b). Thus, some species may face extinction as they may fail to re-establish in areas that are climatically, physiologically, and ecologically suitable (Scott & Lemieux, 2007). Conversely, fast-growing and rapidly dispersing species could flourish (Dukes, 2003; Tilman & Lehman, 2001), resulting in major changes in species' ecological interactions, as well as ecosystem structure and function, which could significantly impact biodiversity (Intergovernmental Panel on Climate Change (IPCC), 2007b; Scott & Lemieux, 2007). In other words, the success of plant species in the future will depend on the rate and magnitude of future climate change, as well as the speed at which plants are able to migrate and adapt in response to those climatic changes (Higgins & Harte, 2007).

Modern-day land-use patterns complicate ecosystem adaptation to climate change by hindering the migration of plants by reducing suitable habitats and creating fragmented landscapes (de Dios et al., 2007; Higgins & Harte, 2007; Iverson et al., 1996; Peters, 1990; Schwartz, 1993). Schwartz (1993) noted that unlike the last postglacial period when trees migrated about 50 kilometers per century through fully forested landscapes, future rates may only be 1-10 kilometers per century in highly fragmented habitats. As a result, the survival of some species, in addition to the protection of ecologically, environmentally, and economically significant areas, may rely more on human activities, such as artificial reforestation programs, than on natural dispersal mechanisms (McKenney et al., 2007; Pitelka, 1997).

3.5 Modeling and Predicting Future Forests

Efforts to predict the consequences of warming temperatures on plant ecosystems, migrations and adaptations throughout the continent have increased as the effects of climate change have become apparent (Andalo, Beaulieu, & Bosquet, 2005; Botkin et al., 2007; Higgins & Harte, 2007; Iverson et al., 2008; Laroque & Smith, 1999; McKenney et al., 2007; Schwartz et al., 2001; J. C. Tardif et al., 2006). In particular, researchers have focused on predicting the range limits and success of individual tree species under projected climate change scenarios. McKenney, Pedlar, Lawrence, Campbell, and Hutchinson (2007) recently studied the potential impacts of climate change on the geographic ranges of 130 tree species throughout North America. The study determined the present-day climatic niches for each of these species, located the conditions for these niches under future climate scenarios using maps, and then indicated where each of the species could potentially occur by the end of the century. The present-day niches for the study species were determined using the Climate Envelope approach through the software program ANUCLIM. To project future climate, the authors ran three GCMs under high (A2) and low (B2) emissions scenarios as defined by the Special Report on Emissions Scenarios (SRES) (Intergovernmental Panel on Climate Change (IPCC), 2007a). Finally, potential future migrations were estimated using “full dispersal” and “no dispersal” situations. The “full dispersal” model allowed tree populations to migrate entirely into their future climate habitat, while the “no dispersal” model assumed that species would be unable to migrate quickly enough to survive, and thus, only exist in areas that overlapped with their current climatic range. Under the “full dispersal” situation, the authors concluded that the average climate envelope size of their study species would decline by 12%, and that the average southern edge of the species ranges would shift approximately 700 Km northward. On the other hand, the “no dispersal” scenario displayed an average climate envelope decrease of 58% and an average range shift of 330 Km northward. The report noted that as the habitats and ranges of species change, important policy concerns regarding assisted migration and forest regeneration projects will arise.

Similarly, Walker, Davis and Sugita (2002) predicted the migrations of multiple tree species through a course model that used bioclimatic variables and species-specific parameters. Specifically, the model STASH (*STAtic SHell)* was used to determine the current and potential future ranges of ten tree species within the Great Lakes region. The model operated by identifying bioclimatic tolerance values for each of the species and then used those values to determine where the species could occur under several emissions scenarios and two GCMs. The authors found that the migrations predicted by the two climate models were similar in direction but different in magnitude, and that future climate changes will affect each of the species uniquely. As a result, they argued that future migrations could have significant economic and ecological implications for the forests in the Great Lakes region and beyond. The report warned that important timber species whose southern limits fall within the region, notably white, jack and red pine (*Pinus strobus* L., *P. banksiana* (Lamb.), and *P. resinosa* (Sol.)) bigtooth aspen (*Populus grandidentata* (Michaux)) and yellow birch (*Betula alleghaniensis* (Britt.)), are predicted to move hundreds of kilometers northwards, while broadleaf trees with current northern range limits within the region, such as black walnut (*Juglans nigra* L.) and black cherry (*Prunus serotina* (Ehrh.)), are projected to gain habitat due to more growing days and increases in coldest-month temperatures (Walker et al., 2002).

Broad-scale tree habitat and migration studies like McKeney et al.'s (2007) and Walker et al.'s (2002) are useful when examining macro-level tree migrations, as well as the potential implications of forthcoming range shifts. These models also raise awareness about climate change impacts, and help direct general climate change adaptation theory, strategy and policy. Broad-scale models, however, cannot effectively influence management and planning decisions at the regional or municipal level, as their outputs are too coarse to be accurately interpreted (Pilkey & Pilkey-Jarvis, 2007), and they fail to account for the local genetic adaptations of forest trees to climate (Laroque, 2005; Morgenstern, 1996). As a result, recent literature has favored finer-scale forestry models (Heller & Zavaleta, 2009; Millar et al., 2007; Pilkey & Pilkey-Jarvis, 2007; Scott et al., 2002; Suffling & Scott, 2002).

Researchers have examined the effects of climate change on individual tree species at more applicable scales through dendroclimatology; a sub-field of dendrochronology that uses dated tree-rings to reconstruct and study past and present climates (Fritts, 1976). Laroque and Smith (2003) conducted a breakthrough study that forecast the radial-growth rates of five high-elevation conifer species on Vancouver Island, British Columbia, Canada. The authors initially created growth-climate relationships between local historical climate data and 88 tree-ring chronologies. Next, coupled GCM outputs and several emissions scenarios were used to estimate future climate for Vancouver Island from 2000 to 2100. Finally, radial-growth forecasts for each species were established by extending the historical growth-climate relationships to 2100 using the GCM data. The authors concluded that each species will react differently to future climate change due to increasing temperatures, shifts in precipitation patterns, and less snow during the winter months.

Likewise, Girardin et al. (2008) forecasted the radial growth response of three tree species to future climates in the Duck Mountain Provincial Forest of Manitoba, Canada. The authors concluded that the radial growth rates for each species would decline under a 2 x CO_2 scenario. The declining radial-growth rates were attributed to drought stress, and the authors warned of decreasing forest productivity within the site.

Besides these two projects, no other researcher was found to have forecast the future radial-growth rates of individual tree species, or to have discussed the usefulness of the method as a planning or management tool. Thus, the following uses the results of the Grand

River Watershed radial-growth forecasts described in chapter two to discuss the implications, perceptions, and limitations of the study on environmental planning and forest management in the region throughout the 21st-century.

3.6 Radial-Growth Forecasting in the Grand River Watershed: Local Management Options and Planning Implications

Recently, the radial-growth rates of sugar maple (*Acer saccharum* L.), eastern hemlock (*Tsuga Canadensis* (L.) Carr.), white pine (*Pinus strobus* L.) and white spruce (*Pica glauca* (Moench.) Voss) within the GRW were forecasted to 2100. The methods closely replicated those of Laroque and Smith (2003), and the results were statically significant. The study indicated that eastern hemlock radial-growth would remain stable throughout the next century, sugar maple and white spruce growth would start to decline, and white pine growth would increase. With these results, managers and planners in the GRW could respond using one or a combination of four general strategies, which range from acquiescent to highly interventionist.

3.6.1 Passive Strategy

By employing a passive strategy, managers and planners in the GRW would simply let nature take its course concerning tree conservation. Suffling and Scott (2002) described this strategy as being based on the belief that ecosystems inherently accommodate climate change, and therefore, should be allowed to adapt without anthropogenic interference. This approach would be the most affordable of all the options in the short-term due to the lack of human intervention. However, if climatic shifts ravage the region’s forests, managers and planners may be forced to take emergency adaptation measures, which would arguably be less effective and more costly than preventative adaptation measures over the long-term (Wilson, 2006). Also, this *laissez-faire* approach could result in irreversible impacts such as species extinction (Scott & Lemieux, 2005), and citizens may be unwilling to accept the actual negative consequences of these passive strategies (Suffling & Scott, 2002). Despite this, passive strategies dominate current policy in the GRW due to lingering uncertainties regarding climate change impacts, a lack of public funds to pursue other options, and a shortage of locally-based forestry research addressing climate change adaptation.

Under a passive approach, sugar maple and white spruce would be left to decline, assuming that no other natural factors counteracted the species' negative response to future climate change. A passive strategy towards sugar maple in the GRW could result in severe consequences, given its abundance in parks and private land throughout the watershed, as well as its significant role in the local maple syrup and timber industries. Conversely, the potential negative ramifications of passive strategies targeting white spruce may not be serious, as the species occurs naturally in only one small pocket of the region. This approach may not be appropriate, however, if the one remaining stand provides vital habitat for a rare or threatened species, if the stand serves a key environmental or economic role that could not be substituted by other tree species, or if the species would be missed by the public.

The projected stability of eastern hemlock and success of white pine in the GRW could have positive or negative effects in the region under a passive strategy. For instance, by not intentionally suppressing the growth or constraining the migration of eastern hemlock and white pine, the species could outcompete those in decline and naturally establish in ecologically or environmentally important areas. As a result, the costs of highly interventionist initiatives, such as species translocation or artificial reforestation projects, could be avoided. Alternatively, if the species were left unbridled, their increasing presence could alter the structure and function of many ecosystems vital to the sustainability and health of surrounding natural and built communities. Until further research is conducted on the capacity of eastern hemlock and white pine seedlings to establish in the climatically modified area, the capability of the species to migrate across highly fragmented landscapes, and the effects of their increasing presence on other plants and animals, the passive strategy should be approached with caution in the GRW throughout the 21st-century. Failure to do so may result in very costly and rushed adaptation measures that may not prove effective when necessary.

3.6.2 Resistance Strategy

Millar, Stephenson, and Stephens (2007) defined resistance strategies as those which work to contain insect infestations, aggressively suppress invasive species, and control fire hazards in an attempt to mitigate the effects of rising temperatures. These options are best applied in the short-term and to forests of high value or those with a low sensitivity to climate (Millar et al., 2007). Importantly, resistance strategies should not be seen as an all-or-nothing approach, as they are often applied to specific stands within a larger management area, and therefore, are generally executed independent of higher-level policy and strategy by public and private woodlot owners.

When choosing which species to target using the resistance approach, decision makers in the GRW must weigh the social, economic, ecological and environmental value of the species, the non-climatic threats facing each of them, and their projected success in the region. Resistance efforts may not be necessary for species that are highly valued, relatively resistant to non-climatic factors, and are projected to remain stable or thrive in the region. Likewise, such strategies may not be appropriate for species of high value that are currently, or will almost certainly be severely affected by a wide-spread insect, pathogen or invasive species for which there is no realistic way of restraining. Also, the resistance approach is probably not worth applying to any species of low value given the resources required. Thus, species that are highly valued and face only low to moderate threats from non-climatic factors would be the sole candidates for resistance strategies.

Planners and managers in the GRW should first determine if sugar maple and white spruce are suitable for resistance strategies due to their projected radial-growth decline. Assuming that no unmanageable non-climatic factors threatened sugar maple in the GRW, important stands of the species could qualify for resistance strategies considering its importance and prevalence. Resistance strategies for white spruce may not be fitting due to its minimal presence and apparent low social, economic, ecological and environmental value in the GRW. With respect to eastern hemlock and white pine, resistance strategies would be ideal only if the two species faced non-climatic challenges that were realistically suppressible, as they are valued in the region and are projected to fair well under future climate change.

3.6.3 Resilience Strategy

Resilience strategies are founded on the notion that plants are most sensitive to climatic changes during the establishment phase, particularly in regards to site suitability (Betancourt, Breshears, & Mulholland, 2004). Activities such as surplus seed-banking (Ledig

& Kitzmiller, 1992) and intensive management during seedling establishment have been shown to enable the retention of desired species even if the site is no longer climatically optimal (Millar et al., 2007; Spittlehouse & Stewart, 2003). The high costs and levels of intervention required for such an approach, however, could require resources and time beyond the scope of government agencies in the GRW. Thus, the implementation of resilience strategies in the region may rely on progressive provincial and federal partnerships dealing with climate change research and adaptation strategy, in addition to public awareness campaigns that teach private landowners how to perform resilience techniques independently.

If supported, authorities and individuals in the GRW could effectively apply resilience strategies to any of the four study species in the short to medium term. Before pursuing this approach, however, background research should first examine the current and projected establishment rates for each species in the watershed. Perhaps test plots using seedlings from the four species could be planted in the southernmost parts of the GRW to replicate drier and warmer conditions. To measure their success under more extreme climate scenarios, the seedlings could also be planted further south in the United States. This exercise would display the capability of the four species to naturally establish under a variety of potential future climates. Additionally, the test plots would let forest managers gauge the levels of intervention necessary to aid in the successful establishment of a species under altered climate if it cannot do so itself. As a result, policymakers could combine this information with the radial-growth forecasts to define those species that (A) require assistance to establish and are projected to decline; (B) species that require assistance to establish but are otherwise projected to remain stable or thrive; (C) species that will establish naturally but are projected to decline; and (D) species that will establish naturally and are projected to remain stable or thrive (Fig. 3.1). If resilience strategies are deemed suitable in the GRW, efforts should be focused on species that fall into category (B). For these species, resources should be directed towards methods that maximize the success of seedling establishment, and in the creation of effective seedling monitoring programs. Resilience strategies would not be recommended for species in the (A) category due to the high risks of failure both in the short and long term. Similarly, resilience strategies may not be appropriate for species in the (D) category, as they may not require assistance to survive. Finally, species in the (C) category could survive in the GRW without resilience strategies, presuming that resistance strategies mitigated the detrimental effects of climate change and the potential pathogens, insects and invasive species that accompany it.

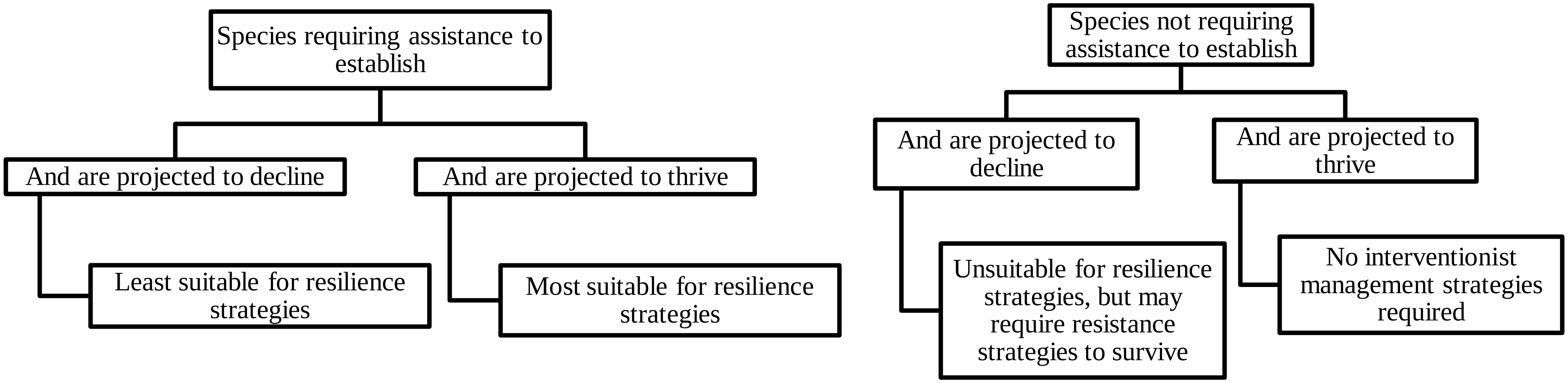


Figure 3.1 A decision tree illustrating the suitability of tree species for resilience strategies if they do or do not require assistance to establish under altered climate scenarios.

3.6.4 Active Management Strategy

Active management strategies maximize the capacity of species and ecological communities to adapt to future climatic changes through a combination of locally-based research and interventionist management practices (Millar et al., 2007; Suffling & Scott, 2002). With accurate knowledge concerning the success of individual tree species under projected climate scenarios, managers and planners could effectively carryout an array of projects that would increase levels of sustainability throughout the GRW. For instance, species projected to succeed, like white pine and eastern hemlock in this case, could be used in the construction of ecological corridors to facilitate the migration of other suitable species (de Dios et al., 2007; Wilby & Perry, 2006). Also, reforestation initiatives could use thriving species to maintain current buffer zones and to protect key environmental features like watersheds (Millar et al., 2007). Conversely, knowledge of species projected to decline could lead to more accurate impact assessments at local and regional scales (Lasch, Lindner, Erhard, Suckow, & Wenzel, 2002), as well as new zoning regulations that would soften the impact of certain land-uses around fragile communities (Solecki & Rosenzweig, 2004; Tompkins & Adger, 2004). Since active strategies work to increase the functionality and adaptability of ecosystems to climate change, they are often grounded in high-level policy aiming to protect and enhance the linkages between natural heritage features and communities. Because these linkages usually cross several jurisdictions, it is essential that all tiers of government work together when implementing active management strategies if the proposed benefits are to be achieved.

Given their narrow and specialized focus, the GRW radial-growth forecasts provide a starting point for planners and managers in the region if active management strategies are ever attempted. The forecasts not only eliminate some uncertainties about climate change impacts, but they could also spur on longer-term and more strategic thinking regarding climate change adaptation techniques (Wilson, 2006). While active strategies are theoretically appealing and offer promise, they require substantial localized research and intensive management practices that would prove costly over the long-term. Also, they are not guaranteed to be effective given the complexities surrounding climate change, and may even result in unforeseen consequences, such as the quicker movement of invasive species and disease through artificial corridors (Scott & Lemieux, 2005; P. Williams et al., 2005).

3.7 The Radial-Growth Forecasting Method: Views and Opinions from Practicing Forest Managers

The GRW radial-growth forecasts were presented to forest managers from the Region of Waterloo, City of Kitchener, RARE Charitable Research Reserve, and the Grand River Conservation Authority to gain insight regarding the implications of the results. While all four managers viewed the radial-growth forecasts as interesting and potentially useful, they also recognized that the results failed to incorporate a host of other factors that would alter the projected success of the species. For instance, all of the managers believed that information concerning seedling dispersal and establishment is critical when predicting the future success of individual tree species, as are the potential effects of invasive species, competition, and disease. Accordingly, they all felt that the radial-growth forecasts will have little effect on policy or strategy within the watershed as an independent piece of research.

Interestingly, one manager suggested that even if these radial-growth forecasts were paired with research covering subjects like seedling dispersal and establishment, they may still lack the capacity to inspire progressive action, as citizens, and subsequently politicians, do not yet view urban and rural forests as assets essential to the health of their communities (Schmitt & Suffling, 2006), nor do they fully appreciate the potential effects and threats of climate change on forested areas. Thus, the lack of necessary ecological information at the regional-level, in conjunction with the current social and political climate, accounts for the limited significance and usage of the GRW radial-growth forecasts at this time.

While the GRW radial-growth forecasts may not result in direct changes to planning or forest management policy now, all the managers agreed that the results could raise awareness about the effects of climate change in the GRW, as well as inspire new ideas regarding future forest management options in the region. Also, two managers mentioned that they would immediately start using white spruce and sugar maple as indicators of climate change impacts, as they are forecast to react negatively to warmer and drier conditions. Finally, one manager noted that these radial-growth forecasts may soon be considered in some tree planting projects, particularly in situations where established trees are transplanted to create or maintain buffer zones along roadways or conflicting land uses.

3.8 Practical Limitations of Radial-Growth Forecasting and Suggestions for Future Research

In addition to the theoretical and technical limitations discussed above, the radial-growth forecasting method is also restricted practically by the large amounts of time, expertise and equipment required to carry out the research. Mature trees first have to be located and sampled, then regional chronologies constructed and standardized. Next, growth-climate relationships must be established, and modeled climate data obtained to forecast radial-growth patterns. All this can take up to one year, making it a large and potentially costly undertaking. Despite these limitations, however, the GRW radial-growth forecasts effectively identified species-specific growth-climate relationships, and used standard modeled climate outputs to predict radial-growth rates.

Three general recommendations for future research are evident after considering this study. First, researchers should explore if it is possible to extrapolate the results of the GRW radial-growth forecasts to other species in the watershed. For instance, would it be reasonable to assume that red pine will thrive since it is commonly found with and closely related to white pine? Perhaps ordination studies (Bray & Curtis, 1957; Hill, 1979; ter Braak & Prentice, 1988), genetic testing or species range maps could provide starting points to address this question. Second, the results of the GRW radial-growth forecasts could be paired with research examining the potential long-term impacts of other factors likely to influence the future success of the four study species, such as dispersal and establishment mechanisms, and the effects of insects, pathogens and competition. This would lead to more accurate growth projections for each of the species, and possibly result in useful guidelines for managers and planners working within the watershed. Finally, comparisons should be drawn between the regional chronologies constructed for the radial-growth forecasting study and those from mature street trees throughout the region. If a correlation exists between the two sets of chronologies, then one might assume that the GRW radial-growth forecasts are also applicable to street trees. Consequently, progressive street tree management practices and policy could be formulated to benefit urban areas by maintaining or enhancing the positive micro-climatic effects that street trees offer (Wilby & Perry, 2006). Street tree forecasts could also lead to new urban design guidelines that would ensure long-lasting, resilient and cost-effective planting projects.

CHAPTER 4: GENERAL CONCLUSIONS

Anthropogenic induced climate change and modern-day land-use patterns could threaten the survival of many tree species throughout the 21^{st}-century. To mitigate the effects of rising temperatures and fragmented landscapes on forested areas, numerous researchers, managers, activists and politicians have started recommending adaptation strategies. Since the effectiveness of these strategies generally relies on the success of individual tree species, efforts have been made to predict the future ranges, habitats and growth-rates of many species at both coarse and fine scales. While broad models offer useful insight regarding the potential impacts and magnitudes of future range shifts, they are often too coarse to be of use for forest managers and environmental planners. As a result, recent literature has favored finer-scale forestry research, particularly when climate change effects are being considered. One method by which researchers have carried out more localized forestry research is through radial-growth forecasting.

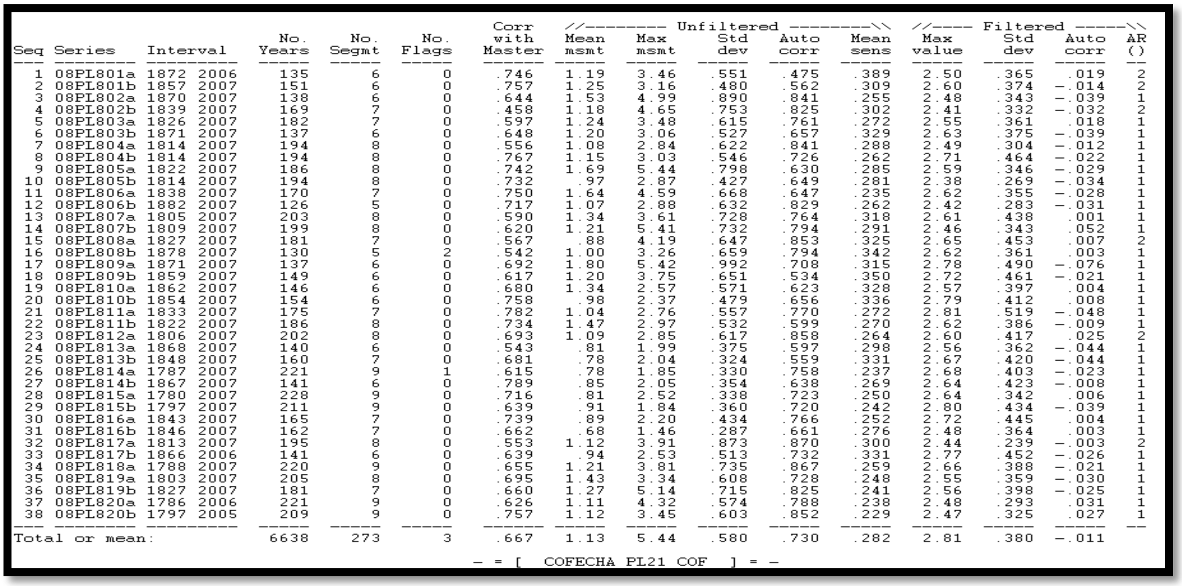
In this instance, radial-growth forecasts were constructed for four tree species common to the Grand River Watershed of Ontario, Canada. Species-specific regional chronologies were first constructed and standardized. Historical growth-climate relationships were then established between the standardized regional chronologies and past climate data from the Guelph OAC weather station. These historical growth-climate relationships were then extended to 2100 using modeled climate data from the Third Generation Coupled Global Model to forecast radial-growth rates. Results indicated that eastern hemlock radial-growth will remain stable throughout the next century, sugar maple and white spruce growth will start to decline, and white pine growth will increase. While the magnitudes of the radial-growth forecasts were amplified by the presence of the previous growth variable, the results were founded on growth-climate relationships that were statically significant and strongly supported in the literature.

Examples of how the radial-growth forecasts could influence planning policy and forest management strategy in the GRW were provided to illustrate the possible linkages between the results and policy formulation. This was important, as connections between technical studies and policy development are often tenuous (Dessler & Parson, 2006). To gage the practical implications, perceptions and limitations of the radial-growth forecasts on planning and management in the Grand River Watershed, the results were presented to four forest managers working in the area. All the managers found the radial-growth forecasts interesting, as they provided new information regarding climate change impacts. As an independent piece of research, however, the managers agreed that the radial-growth forecasts would not likely impact policy or strategy in the watershed, as the results could not account for a host of other factors that would certainly impact the future success of the study species. As a result, it was recommended that future research should work to extrapolate the results of the radial-growth forecasts to more tree species and types throughout the GRW, as well as begin to incorporate other climatic and non-climatic factors into the models, so that more accurate and useful growth projections can be constructed in the watershed.

Appendix A

Cross-Dated Eastern Hemlock Individual Site Chronologies (Accessible through the International Tree-Ring Databank as of Jan. 1, 2010)

Homer Watson (08PL800's)



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  1 08PL801a 1872 2006    135      6      0     .746   1.19   3.46   .551   .475   .389   2.50   .365   .019   2
  2 08PL801b 1857 2007    151      6      0     .757   1.25   3.16   .480   .562   .309   2.60   .374  -.014   2
  3 08PL802a 1870 2007    138      6      0     .644   1.53   4.99   .890   .841   .255   2.48   .343  -.039   1
  4 08PL802b 1839 2007    169      7      0     .458   1.18   4.65   .753   .825   .302   2.41   .332  -.032   2
  5 08PL803a 1826 2007    182      7      0     .597   1.24   3.48   .615   .761   .272   2.55   .361   .018   1
  6 08PL803b 1871 2007    137      6      0     .648   1.20   3.06   .527   .657   .329   2.63   .375  -.039   1
  7 08PL804a 1814 2007    194      8      0     .556   1.08   2.84   .622   .841   .288   2.49   .304  -.012   1
  8 08PL804b 1814 2007    194      8      0     .767   1.15   3.03   .546   .726   .262   2.71   .464  -.022   1
  9 08PL805a 1822 2007    186      8      0     .742   1.69   5.44   .798   .630   .285   2.59   .346  -.029   1
 10 08PL805b 1814 2007    194      8      0     .732    .97   2.87   .427   .649   .281   2.38   .269  -.034   1
 11 08PL806a 1838 2007    170      7      0     .750   1.64   4.59   .668   .647   .235   2.62   .355  -.028   1
 12 08PL806b 1882 2007    126      5      0     .717   1.07   2.88   .632   .829   .262   2.42   .283  -.031   1
 13 08PL807a 1805 2007    203      8      0     .590   1.34   3.61   .728   .764   .318   2.61   .438   .001   1
 14 08PL807b 1809 2007    199      8      0     .620   1.21   5.41   .732   .794   .291   2.46   .343   .052   1
 15 08PL808a 1827 2007    181      7      0     .567    .88   4.19   .647   .853   .325   2.65   .453   .007   2
 16 08PL808b 1878 2007    130      5      2     .542   1.00   3.26   .659   .794   .342   2.62   .361   .003   1
 17 08PL809a 1871 2007    137      6      0     .692   1.80   5.42   .992   .708   .315   2.78   .490  -.076   1
 18 08PL809b 1859 2007    149      6      0     .617   1.20   3.75   .651   .534   .350   2.72   .461  -.021   1
 19 08PL810a 1862 2007    146      6      0     .680   1.34   2.57   .571   .623   .328   2.57   .397   .004   1
 20 08PL810b 1854 2007    154      6      0     .758    .98   2.37   .479   .656   .336   2.79   .412   .008   1
 21 08PL811a 1833 2007    175      7      0     .782   1.04   2.76   .557   .770   .272   2.81   .519  -.048   1
 22 08PL811b 1822 2007    186      8      0     .734   1.47   2.97   .532   .599   .270   2.62   .386  -.009   1
 23 08PL812a 1806 2007    202      8      0     .693   1.09   2.85   .617   .858   .264   2.60   .417   .025   2
 24 08PL813a 1868 2007    140      6      0     .543    .81   1.99   .375   .597   .298   2.56   .362  -.044   1
 25 08PL813b 1848 2007    160      7      0     .681    .78   2.04   .324   .559   .331   2.67   .420  -.044   1
 26 08PL814a 1787 2007    221      9      1     .615    .78   1.85   .330   .758   .237   2.68   .403  -.023   1
 27 08PL814b 1867 2007    141      6      0     .789    .85   2.05   .354   .638   .269   2.64   .423  -.008   1
 28 08PL815a 1780 2007    228      9      0     .716    .81   2.52   .338   .723   .250   2.64   .342   .006   1
 29 08PL815b 1797 2007    211      9      0     .639    .91   1.84   .360   .720   .242   2.80   .434  -.039   1
 30 08PL816a 1843 2007    165      7      0     .739    .89   2.20   .434   .766   .252   2.72   .445   .004   1
 31 08PL816b 1846 2007    162      7      0     .662    .68   1.46   .287   .661   .276   2.48   .364   .003   1
 32 08PL817a 1813 2007    195      8      0     .553   1.12   3.91   .873   .870   .300   2.44   .239  -.003   2
 33 08PL817b 1866 2006    141      6      0     .639    .94   2.53   .513   .732   .331   2.77   .452  -.026   1
 34 08PL818a 1788 2007    220      9      0     .655   1.21   3.81   .735   .867   .259   2.66   .388  -.021   1
 35 08PL819a 1803 2007    205      8      0     .695   1.43   3.34   .608   .728   .248   2.55   .359  -.030   1
 36 08PL819b 1827 2007    181      7      0     .660   1.27   5.14   .715   .825   .241   2.56   .398  -.025   1
 37 08PL820a 1786 2006    221      9      0     .626   1.11   4.32   .574   .788   .238   2.48   .293   .031   1
 38 08PL820b 1797 2005    209      9      0     .757   1.12   3.45   .603   .852   .229   2.47   .325   .027   1
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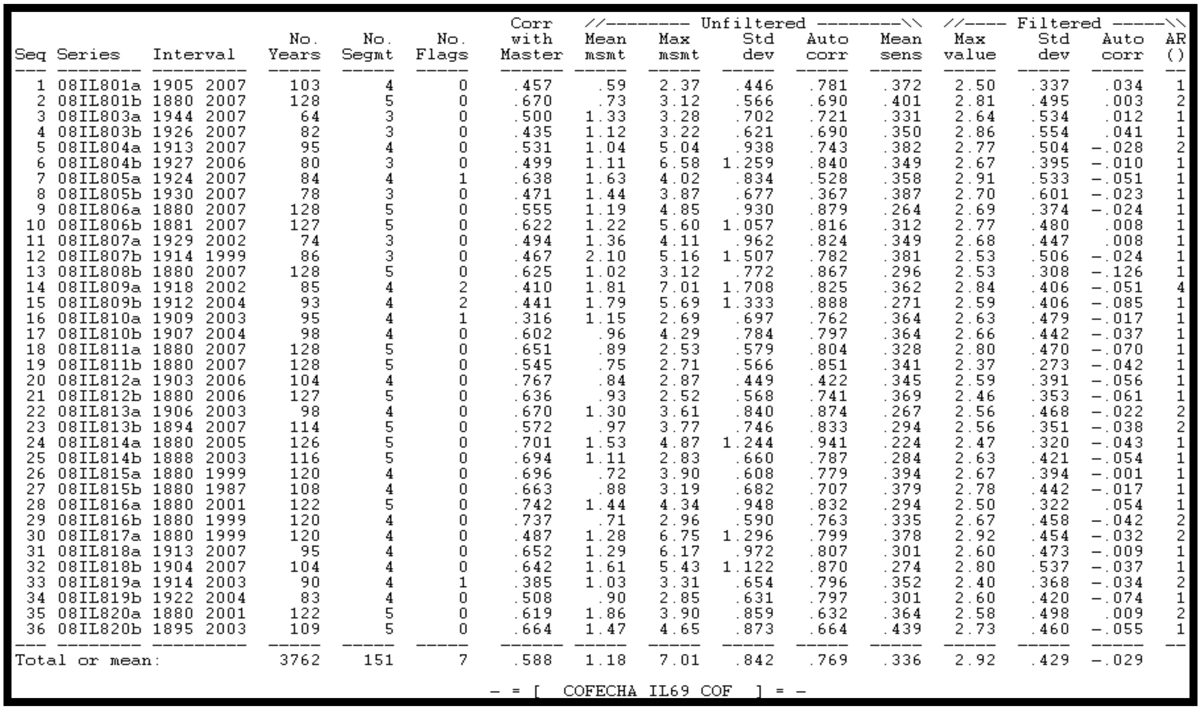
Luther Marsh (08IL800's)



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  7 08IL805a 1924 2007     84      4      1     .638   1.63   4.02   .834   .528   .358   2.91   .533  -.051   1
  8 08IL805b 1930 2007     78      3      0     .471   1.44   3.87   .677   .367   .387   2.70   .601  -.023   1
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 10 08IL806b 1881 2007    127      5      0     .622   1.22   5.60  1.057   .816   .312   2.77   .480   .008   1
 11 08IL807a 1929 2002     74      3      0     .494   1.36   4.11   .962   .824   .349   2.68   .447   .008   1
 12 08IL807b 1914 1999     86      3      0     .467   2.10   5.16  1.507   .782   .381   2.53   .506  -.024   1
 13 08IL808b 1880 2007    128      5      0     .625   1.02   3.12   .772   .867   .296   2.53   .308  -.126   1
 14 08IL809a 1918 2002     85      4      2     .410   1.81   7.01  1.708   .825   .362   2.84   .406  -.051   4
 15 08IL809b 1912 2004     93      4      2     .441   1.79   5.69  1.333   .888   .271   2.59   .406  -.085   1
 16 08IL810a 1909 2003     95      4      1     .316   1.15   2.69   .697   .762   .364   2.63   .479  -.017   1
 17 08IL810b 1907 2004     98      4      0     .602    .96   4.29   .784   .797   .364   2.66   .442  -.037   1
 18 08IL811a 1880 2007    128      5      0     .651    .89   2.53   .579   .804   .328   2.80   .470  -.070   1
 19 08IL811b 1880 2007    128      5      0     .545    .75   2.71   .566   .851   .341   2.37   .273  -.042   1
 20 08IL812a 1903 2006    104      4      0     .767    .84   2.87   .449   .422   .345   2.59   .391  -.056   1
 21 08IL812b 1880 2006    127      5      0     .636    .93   2.52   .568   .741   .369   2.46   .353  -.061   1
 22 08IL813a 1906 2003     98      4      0     .670   1.30   3.61   .840   .874   .267   2.56   .468  -.022   2
 23 08IL813b 1894 2007    114      5      0     .572    .97   3.77   .746   .833   .294   2.56   .351  -.038   2
 24 08IL814a 1880 2005    126      5      0     .701   1.53   4.87  1.244   .941   .224   2.47   .320  -.043   1
 25 08IL814b 1888 2003    116      5      0     .694   1.11   2.83   .660   .787   .284   2.63   .421  -.054   1
 26 08IL815a 1880 1999    120      4      0     .696    .72   3.90   .608   .779   .394   2.67   .394  -.001   1
 27 08IL815b 1880 1987    108      4      0     .663    .88   3.19   .682   .707   .379   2.78   .442  -.017   1
 28 08IL816a 1880 2001    122      5      0     .742   1.44   4.34   .948   .832   .294   2.50   .322   .054   1
 29 08IL816b 1880 1999    120      4      0     .737    .71   2.96   .590   .763   .335   2.67   .458  -.042   2
 30 08IL817a 1880 1999    120      4      0     .487   1.28   6.75  1.296   .799   .378   2.92   .454  -.032   2
 31 08IL818a 1913 2007     95      4      0     .652   1.29   6.17   .972   .807   .301   2.60   .473  -.009   1
 32 08IL818b 1904 2007    104      4      0     .642   1.61   5.43  1.122   .870   .274   2.80   .537  -.037   1
 33 08IL819a 1914 2003     90      4      1     .385   1.03   3.31   .654   .796   .352   2.40   .368  -.034   2
 34 08IL819b 1922 2004     83      4      0     .508    .90   2.85   .631   .797   .301   2.60   .420  -.074   1
 35 08IL820a 1880 2001    122      5      0     .619   1.86   3.90   .859   .632   .364   2.58   .498   .009   2
 36 08IL820b 1895 2003    109      5      0     .664   1.47   4.65   .873   .664   .439   2.73   .460  -.055   1
--- -------- ---------  -----  -----  -----   ------  -----  -----  -----  -----  -----  -----  -----  -----  --
Total or mean:           3762    151      7     .588   1.18   7.01   .842   .769   .336   2.92   .429  -.029

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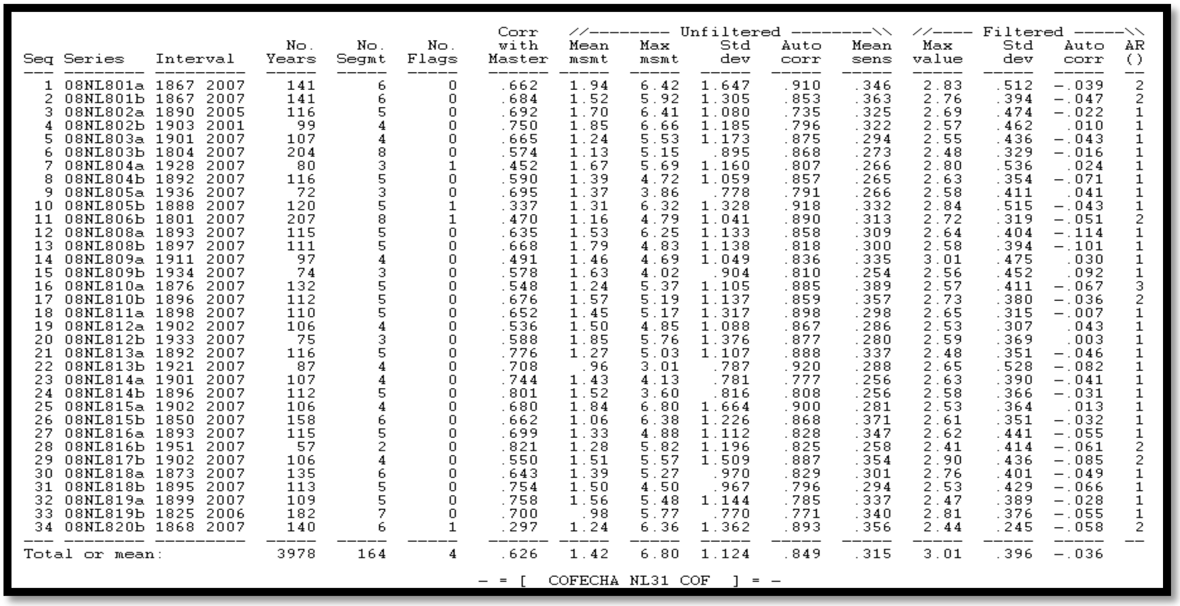
Oakland Swamp (08NL800's)



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                                                Corr  //-------- Unfiltered --------\\  //---- Filtered -----\\
                             No.    No.    No.  with   Mean    Max    Std   Auto   Mean    Max    Std   Auto  AR
Seq Series   Interval      Years  Segmt  Flags  Master msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- ---------     -----  -----  -----  ------ -----  -----  -----  -----  -----  -----  -----  -----  --
  1 08NL801a 1867 2007       141      6      0   .662  1.94   6.42  1.647   .910   .346   2.83   .512  -.039   2
  2 08NL801b 1867 2007       141      6      0   .684  1.52   5.92  1.305   .853   .363   2.76   .394  -.047   2
  3 08NL802a 1890 2005       116      5      0   .692  1.70   6.41  1.080   .735   .325   2.69   .474  -.022   1
  4 08NL802b 1903 2001        99      4      0   .750  1.85   6.66  1.185   .796   .322   2.57   .462   .010   1
  5 08NL803a 1901 2007       107      4      0   .665  1.24   5.53  1.173   .875   .294   2.55   .436  -.043   1
  6 08NL803b 1804 2007       204      8      0   .574  1.13   5.15   .895   .868   .273   2.48   .329  -.016   1
  7 08NL804a 1928 2007        80      3      1   .452  1.67   5.69  1.160   .807   .266   2.80   .536   .024   1
  8 08NL804b 1892 2007       116      5      0   .590  1.39   4.72  1.059   .857   .265   2.63   .354  -.071   1
  9 08NL805a 1936 2007        72      3      0   .695  1.37   3.86   .778   .791   .266   2.58   .411   .041   1
 10 08NL805b 1888 2007       120      5      1   .337  1.31   6.32  1.328   .918   .332   2.84   .515  -.043   1
 11 08NL806b 1801 2007       207      8      1   .470  1.16   4.79  1.041   .890   .313   2.72   .319  -.051   2
 12 08NL808a 1893 2007       115      5      0   .635  1.53   6.25  1.133   .858   .309   2.64   .404  -.114   1
 13 08NL808b 1897 2007       111      5      0   .668  1.79   4.83  1.138   .818   .300   2.58   .394  -.101   1
 14 08NL809a 1911 2007        97      4      0   .491  1.46   4.69  1.049   .836   .335   3.01   .475   .030   1
 15 08NL809b 1934 2007        74      3      0   .578  1.63   4.02   .904   .810   .254   2.56   .452   .092   1
 16 08NL810a 1876 2007       132      5      0   .548  1.24   5.37  1.105   .885   .389   2.57   .411  -.067   3
 17 08NL810b 1896 2007       112      5      0   .676  1.57   5.19  1.137   .859   .357   2.73   .380  -.036   2
 18 08NL811a 1898 2007       110      5      0   .652  1.45   5.17  1.317   .898   .298   2.65   .315  -.007   1
 19 08NL812a 1902 2007       106      4      0   .536  1.50   4.85  1.088   .867   .286   2.53   .307   .043   1
 20 08NL812b 1933 2007        75      3      0   .588  1.85   5.76  1.376   .877   .280   2.59   .369   .003   1
 21 08NL813a 1892 2007       116      5      0   .776  1.27   5.03  1.107   .888   .337   2.48   .351  -.046   1
 22 08NL813b 1921 2007        87      4      0   .708   .96   3.01   .787   .920   .288   2.65   .528  -.082   1
 23 08NL814a 1901 2007       107      4      0   .744  1.43   4.13   .781   .777   .256   2.63   .390  -.041   1
 24 08NL814b 1896 2007       112      5      0   .801  1.52   3.60   .816   .808   .256   2.58   .366  -.031   1
 25 08NL815a 1902 2007       106      4      0   .680  1.84   6.80  1.664   .900   .281   2.53   .364   .013   1
 26 08NL815b 1850 2007       158      6      0   .662  1.06   6.38  1.226   .868   .371   2.61   .351  -.032   1
 27 08NL816a 1893 2007       115      5      0   .699  1.33   4.88  1.112   .828   .347   2.62   .441  -.055   1
 28 08NL816b 1951 2007        57      2      0   .821  1.28   5.82  1.196   .825   .258   2.41   .414  -.061   2
 29 08NL817b 1902 2007       106      4      0   .550  1.51   5.57  1.509   .887   .354   2.90   .436  -.085   2
 30 08NL818a 1873 2007       135      6      0   .643  1.39   5.27   .970   .829   .301   2.76   .401  -.049   1
 31 08NL818b 1895 2007       113      5      0   .754  1.50   4.50   .967   .796   .294   2.53   .429  -.066   1
 32 08NL819a 1899 2007       109      5      0   .758  1.56   5.48  1.144   .785   .337   2.47   .389  -.028   1
 33 08NL819b 1825 2006       182      7      0   .700   .98   5.77   .770   .771   .340   2.81   .376  -.055   1
 34 08NL820b 1868 2007       140      6      1   .297  1.24   6.36  1.362   .893   .356   2.44   .245  -.058   2
--- -------- ---------     -----  -----  -----  ------ -----  -----  -----  -----  -----  -----  -----  -----  --
Total or mean:              3978    164      4   .626  1.42   6.80  1.124   .849   .315   3.01   .396  -.036

                                     - = [  COFECHA NL31 COF  ] = -
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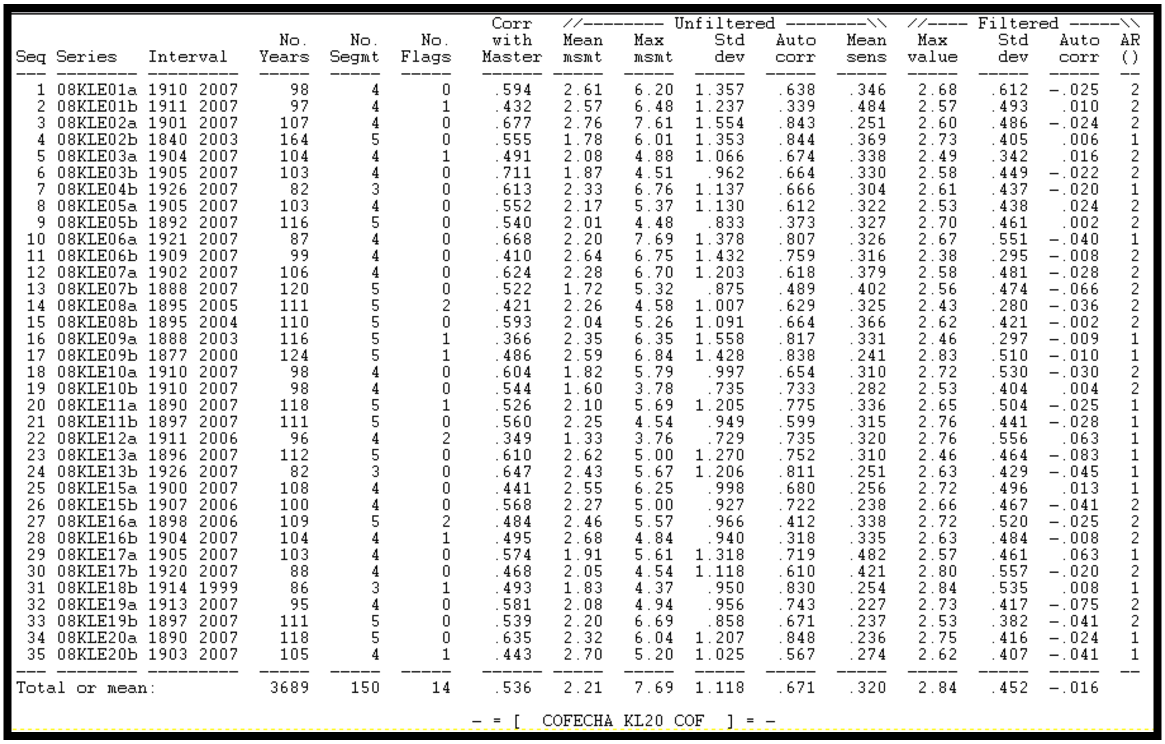
Cross-Dated Sugar Maple Individual Site Chronologies

Guelph Lake (08KLE00's)



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                                                Corr  //-------- Unfiltered --------\\  //---- Filtered -----\\
                             No.    No.    No.  with   Mean    Max    Std   Auto   Mean    Max    Std   Auto  AR
Seq Series   Interval      Years  Segmt  Flags  Master msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- ---------     -----  -----  -----  ------ -----  -----  -----  -----  -----  -----  -----  -----  --
  1 08KLE01a 1910 2007        98      4      0   .594  2.61   6.20  1.357   .638   .346   2.68   .612  -.025   2
  2 08KLE01b 1911 2007        97      4      1   .432  2.57   6.48  1.237   .339   .484   2.57   .493   .010   2
  3 08KLE02a 1901 2007       107      4      0   .677  2.76   7.61  1.554   .843   .251   2.60   .486  -.024   2
  4 08KLE02b 1840 2003       164      5      0   .555  1.78   6.01  1.353   .844   .369   2.73   .405   .006   1
  5 08KLE03a 1904 2007       104      4      1   .491  2.08   4.88  1.066   .674   .338   2.49   .342   .016   2
  6 08KLE03b 1905 2007       103      4      0   .711  1.87   4.51   .962   .664   .330   2.58   .449  -.022   2
  7 08KLE04b 1926 2007        82      3      0   .613  2.33   6.76  1.137   .666   .304   2.61   .437  -.020   1
  8 08KLE05a 1905 2007       103      4      0   .552  2.17   5.37  1.130   .612   .322   2.53   .438   .024   2
  9 08KLE05b 1892 2007       116      5      0   .540  2.01   4.48   .833   .373   .327   2.70   .461   .002   2
 10 08KLE06a 1921 2007        87      4      0   .668  2.20   7.69  1.378   .807   .326   2.67   .551  -.040   1
 11 08KLE06b 1909 2007        99      4      0   .410  2.64   6.75  1.432   .759   .316   2.38   .295  -.008   2
 12 08KLE07a 1902 2007       106      4      0   .624  2.28   6.70  1.203   .618   .379   2.58   .481  -.028   2
 13 08KLE07b 1888 2007       120      5      0   .522  1.72   5.32   .875   .489   .402   2.56   .474  -.066   2
 14 08KLE08a 1895 2005       111      5      2   .421  2.26   4.58  1.007   .629   .325   2.43   .280  -.036   2
 15 08KLE08b 1895 2004       110      5      0   .593  2.04   5.26  1.091   .664   .366   2.62   .421  -.002   2
 16 08KLE09a 1888 2003       116      5      1   .366  2.35   6.35  1.558   .817   .331   2.46   .297  -.009   1
 17 08KLE09b 1877 2000       124      5      1   .486  2.59   6.84  1.428   .838   .241   2.83   .510  -.010   1
 18 08KLE10a 1910 2007        98      4      0   .604  1.82   5.79   .997   .654   .310   2.72   .530  -.030   2
 19 08KLE10b 1910 2007        98      4      0   .544  1.60   3.78   .735   .733   .282   2.53   .404   .004   2
 20 08KLE11a 1890 2007       118      5      1   .526  2.10   5.69  1.205   .775   .336   2.65   .504  -.025   1
 21 08KLE11b 1897 2007       111      5      0   .560  2.25   4.54   .949   .599   .315   2.76   .441  -.028   1
 22 08KLE12a 1911 2006        96      4      2   .349  1.33   3.76   .729   .735   .320   2.76   .556   .063   1
 23 08KLE13a 1896 2007       112      5      0   .610  2.62   5.00  1.270   .752   .310   2.46   .464  -.083   1
 24 08KLE13b 1926 2007        82      3      0   .647  2.43   5.67  1.206   .811   .251   2.63   .429  -.045   1
 25 08KLE15a 1900 2007       108      4      0   .441  2.55   6.25   .998   .680   .256   2.72   .496   .013   1
 26 08KLE15b 1907 2006       100      4      0   .568  2.27   5.00   .927   .722   .238   2.66   .467  -.041   2
 27 08KLE16a 1898 2006       109      5      2   .484  2.46   5.57   .966   .412   .338   2.72   .520  -.025   2
 28 08KLE16b 1904 2007       104      4      1   .495  2.68   4.84   .940   .318   .335   2.63   .484  -.008   2
 29 08KLE17a 1905 2007       103      4      0   .574  1.91   5.61  1.318   .719   .482   2.57   .461   .063   1
 30 08KLE17b 1920 2007        88      4      0   .468  2.05   4.54  1.118   .610   .421   2.80   .557  -.020   2
 31 08KLE18b 1914 1999        86      3      1   .493  1.83   4.37   .950   .830   .254   2.84   .535   .008   1
 32 08KLE19a 1913 2007        95      4      0   .581  2.08   4.94   .956   .743   .227   2.73   .417  -.075   2
 33 08KLE19b 1897 2007       111      5      0   .539  2.20   6.69   .858   .671   .237   2.53   .382  -.041   2
 34 08KLE20a 1890 2007       118      5      0   .635  2.32   6.04  1.207   .848   .236   2.75   .416  -.024   1
 35 08KLE20b 1903 2007       105      4      1   .443  2.70   5.20  1.025   .567   .274   2.62   .407  -.041   1
--- -------- ---------     -----  -----  -----  ------ -----  -----  -----  -----  -----  -----  -----  -----  --
Total or mean:              3689    150     14   .536  2.21   7.69  1.118   .671   .320   2.84   .452  -.016

                                     - = [  COFECHA KL20 COF  ] = -
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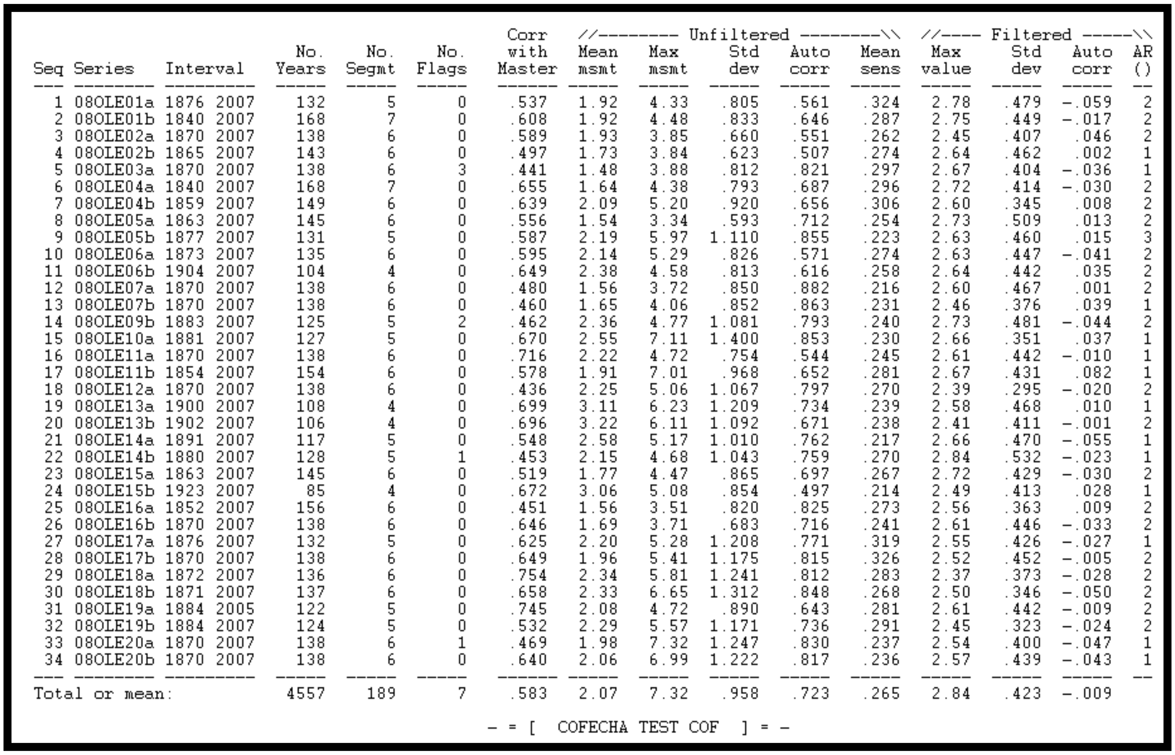
Indian Woods (08OLE00’s)



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                                                Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                          No.    No.    No.     with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
Seq Series   Interval    Years  Segmt  Flags   Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- ---------   -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
  1 08OLE01a 1876 2007     132      5      0     .537  1.92   4.33   .805   .561   .324   2.78   .479  -.059   2
  2 08OLE01b 1840 2007     168      7      0     .608  1.92   4.48   .833   .646   .287   2.75   .449  -.017   2
  3 08OLE02a 1870 2007     138      6      0     .589  1.93   3.85   .660   .551   .262   2.45   .407   .046   2
  4 08OLE02b 1865 2007     143      6      0     .497  1.73   3.84   .623   .507   .274   2.64   .462   .002   1
  5 08OLE03a 1870 2007     138      6      3     .441  1.48   3.88   .812   .821   .297   2.67   .404  -.036   1
  6 08OLE04a 1840 2007     168      7      0     .655  1.64   4.38   .793   .687   .296   2.72   .414  -.030   2
  7 08OLE04b 1859 2007     149      6      0     .639  2.09   5.20   .920   .656   .306   2.60   .345   .008   2
  8 08OLE05a 1863 2007     145      6      0     .556  1.54   3.34   .593   .712   .254   2.73   .509   .013   2
  9 08OLE05b 1877 2007     131      5      0     .587  2.19   5.97  1.110   .855   .223   2.63   .460   .015   3
 10 08OLE06a 1873 2007     135      6      0     .595  2.14   5.29   .826   .571   .274   2.63   .447  -.041   2
 11 08OLE06b 1904 2007     104      4      0     .649  2.38   4.58   .813   .616   .258   2.64   .442   .035   2
 12 08OLE07a 1870 2007     138      6      0     .480  1.56   3.72   .850   .882   .216   2.60   .467   .001   2
 13 08OLE07b 1870 2007     138      6      0     .460  1.65   4.06   .852   .863   .231   2.46   .376   .039   1
 14 08OLE09b 1883 2007     125      5      2     .462  2.36   4.77  1.081   .793   .240   2.73   .481  -.044   2
 15 08OLE10a 1881 2007     127      5      0     .670  2.55   7.11  1.400   .853   .230   2.66   .351   .037   1
 16 08OLE11a 1870 2007     138      6      0     .716  2.22   4.72   .754   .544   .245   2.61   .442  -.010   1
 17 08OLE11b 1854 2007     154      6      0     .578  1.91   7.01   .968   .652   .281   2.67   .431   .082   1
 18 08OLE12a 1870 2007     138      6      0     .436  2.25   5.06  1.067   .797   .270   2.39   .295  -.020   2
 19 08OLE13a 1900 2007     108      4      0     .699  3.11   6.23  1.209   .734   .239   2.58   .468   .010   1
 20 08OLE13b 1902 2007     106      4      0     .696  3.22   6.11  1.092   .671   .238   2.41   .411  -.001   2
 21 08OLE14a 1891 2007     117      5      0     .548  2.58   5.17  1.010   .762   .217   2.66   .470  -.055   1
 22 08OLE14b 1880 2007     128      5      1     .453  2.15   4.68  1.043   .759   .270   2.84   .532  -.023   1
 23 08OLE15a 1863 2007     145      6      0     .519  1.77   4.47   .865   .697   .267   2.72   .429  -.030   2
 24 08OLE15b 1923 2007      85      4      0     .672  3.06   5.08   .854   .497   .214   2.49   .413   .028   1
 25 08OLE16a 1852 2007     156      6      0     .451  1.56   3.51   .820   .825   .273   2.56   .363   .009   2
 26 08OLE16b 1870 2007     138      6      0     .646  1.69   3.71   .683   .716   .241   2.61   .446  -.033   2
 27 08OLE17a 1876 2007     132      5      0     .625  2.20   5.28  1.208   .771   .319   2.55   .426  -.027   1
 28 08OLE17b 1870 2007     138      6      0     .649  1.96   5.41  1.175   .815   .326   2.52   .452  -.005   2
 29 08OLE18a 1872 2007     136      6      0     .754  2.34   5.81  1.241   .812   .283   2.37   .373  -.028   2
 30 08OLE18b 1871 2007     137      6      0     .658  2.33   6.65  1.312   .848   .268   2.50   .346  -.050   2
 31 08OLE19a 1884 2005     122      5      0     .745  2.08   4.72   .890   .643   .281   2.61   .442  -.009   2
 32 08OLE19b 1884 2007     124      5      0     .532  2.29   5.57  1.171   .736   .291   2.45   .323  -.024   2
 33 08OLE20a 1870 2007     138      6      1     .469  1.98   7.32  1.247   .830   .237   2.54   .400  -.047   1
 34 08OLE20b 1870 2007     138      6      0     .640  2.06   6.99  1.222   .817   .236   2.57   .439  -.043   1
--- -------- ---------   -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
Total or mean:            4557    189      7     .583  2.07   7.32   .958   .723   .265   2.84   .423  -.009

                                          - = [  COFECHA TEST COF  ] = -
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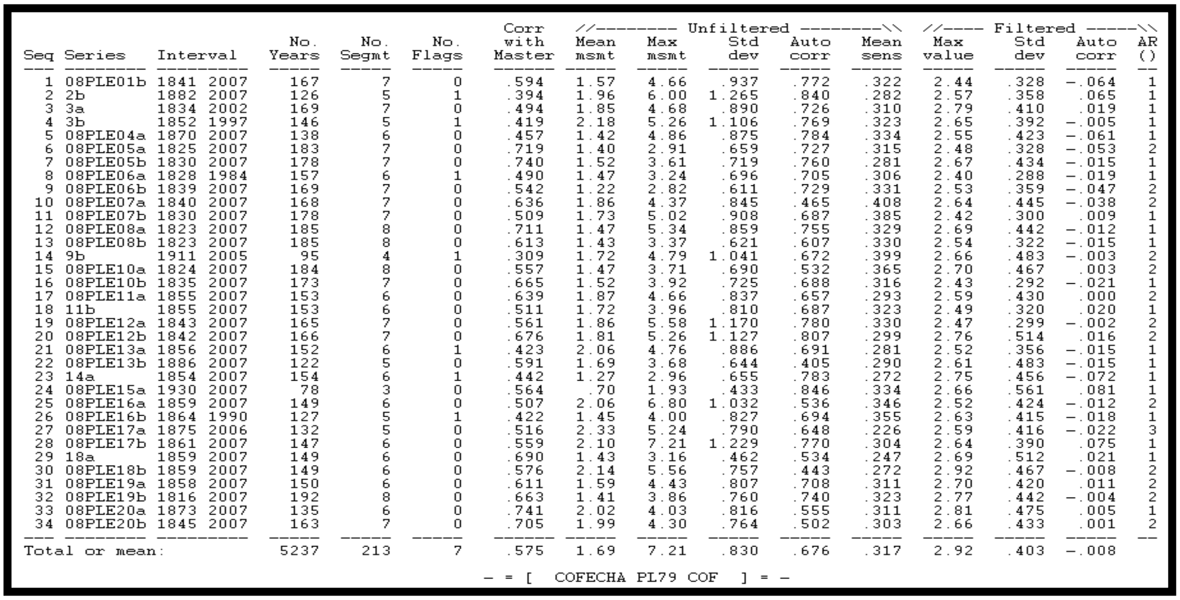
Homer Watson (08PLE00’s)



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                          No.    No.    No.     with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
Seq Series    Interval   Years  Segmt  Flags   Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- --------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
  1 08PLE01b 1841 2007     167      7      0     .594  1.57   4.66   .937   .772   .322   2.44   .328  -.064   1
  2 2b       1882 2007     126      5      1     .394  1.96   6.00  1.265   .840   .282   2.57   .358   .065   1
  3 3a       1834 2002     169      7      0     .494  1.85   4.68   .890   .726   .310   2.79   .410   .019   1
  4 3b       1852 1997     146      5      1     .419  2.18   5.26  1.106   .769   .323   2.65   .392  -.005   1
  5 08PLE04a 1870 2007     138      6      0     .457  1.42   4.86   .875   .784   .334   2.55   .423  -.061   1
  6 08PLE05a 1825 2007     183      7      0     .719  1.40   2.91   .659   .727   .315   2.48   .328  -.053   2
  7 08PLE05b 1830 2007     178      7      0     .740  1.52   3.61   .719   .760   .281   2.67   .434  -.015   1
  8 08PLE06a 1828 1984     157      6      1     .490  1.47   3.24   .696   .705   .306   2.40   .288  -.019   1
  9 08PLE06b 1839 2007     169      7      0     .542  1.22   2.82   .611   .729   .331   2.53   .359  -.047   2
 10 08PLE07a 1840 2007     168      7      0     .636  1.86   4.37   .845   .465   .408   2.64   .445  -.038   2
 11 08PLE07b 1830 2007     178      7      0     .509  1.73   5.02   .908   .687   .385   2.42   .300   .009   1
 12 08PLE08a 1823 2007     185      8      0     .711  1.47   5.34   .859   .755   .329   2.69   .442  -.012   1
 13 08PLE08b 1823 2007     185      8      0     .613  1.43   3.37   .621   .607   .330   2.54   .322  -.015   1
 14 9b       1911 2005      95      4      1     .309  1.72   4.79  1.041   .672   .399   2.66   .483  -.003   2
 15 08PLE10a 1824 2007     184      8      0     .557  1.47   3.71   .690   .532   .365   2.70   .467   .003   2
 16 08PLE10b 1835 2007     173      7      0     .665  1.52   3.92   .725   .688   .316   2.43   .292  -.021   1
 17 08PLE11a 1855 2007     153      6      0     .639  1.87   4.66   .837   .657   .293   2.59   .430   .000   2
 18 11b      1855 2007     153      6      0     .511  1.72   3.96   .810   .687   .323   2.49   .320   .020   1
 19 08PLE12a 1843 2007     165      7      0     .561  1.86   5.58  1.170   .780   .330   2.47   .299  -.002   2
 20 08PLE12b 1842 2007     166      7      0     .676  1.81   5.26  1.127   .807   .299   2.76   .514   .016   2
 21 08PLE13a 1856 2007     152      6      1     .423  2.06   4.76   .886   .691   .281   2.52   .356  -.015   1
 22 08PLE13b 1886 2007     122      5      0     .591  1.69   3.68   .644   .405   .290   2.61   .483  -.015   1
 23 14a      1854 2007     154      6      1     .442  1.27   2.96   .655   .783   .272   2.75   .456  -.072   1
 24 08PLE15a 1930 2007      78      3      0     .564   .70   1.93   .433   .846   .334   2.66   .561   .081   1
 25 08PLE16a 1859 2007     149      6      0     .507  2.06   6.80  1.032   .536   .346   2.52   .424  -.012   2
 26 08PLE16b 1864 1990     127      5      1     .422  1.45   4.00   .827   .694   .355   2.63   .415  -.018   1
 27 08PLE17a 1875 2006     132      5      0     .516  2.33   5.24   .790   .648   .226   2.59   .416  -.022   3
 28 08PLE17b 1861 2007     147      6      0     .559  2.10   7.21  1.229   .770   .304   2.64   .390   .075   1
 29 18a      1859 2007     149      6      0     .690  1.43   3.16   .462   .534   .247   2.69   .512   .021   1
 30 08PLE18b 1859 2007     149      6      0     .576  2.14   5.56   .757   .443   .272   2.92   .467  -.008   2
 31 08PLE19a 1858 2007     150      6      0     .611  1.59   4.43   .807   .708   .311   2.70   .420   .011   2
 32 08PLE19b 1816 2007     192      8      0     .663  1.41   3.86   .760   .740   .323   2.77   .442  -.004   2
 33 08PLE20a 1873 2007     135      6      0     .741  2.02   4.03   .816   .555   .311   2.81   .475   .005   1
 34 08PLE20b 1845 2007     163      7      0     .705  1.99   4.30   .764   .502   .303   2.66   .433   .001   2
--- --------- ---------  -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
Total or mean:            5237    213      7     .575  1.69   7.21   .830   .676   .317   2.92   .403  -.008

                                          - = [  COFECHA PL79 COF  ] = -
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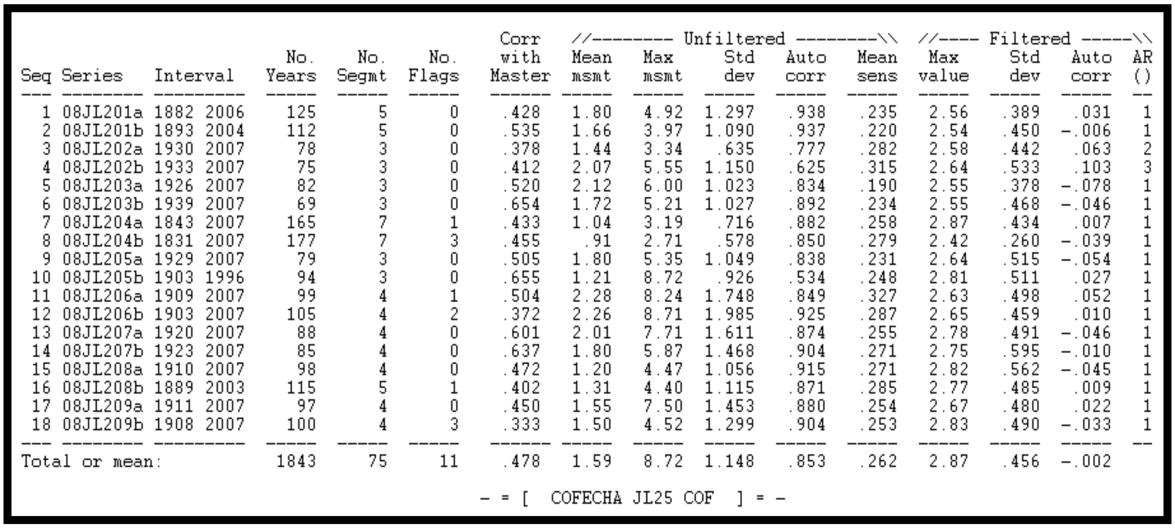
Cross-Dated White Spruce Individual Site Chronology

Eramosa River



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                                               Corr  //-------- Unfiltered --------\\  //---- Filtered -----\\
                         No.    No.    No.     with  Mean    Max    Std   Auto   Mean    Max    Std   Auto  AR
Seq Series   Interval  Years  Segmt  Flags   Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- --------- -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
  1 08JL201a 1882 2006   125      5      0     .428  1.80   4.92  1.297   .938   .235   2.56   .389   .031   1
  2 08JL201b 1893 2004   112      5      0     .535  1.66   3.97  1.090   .937   .220   2.54   .450  -.006   1
  3 08JL202a 1930 2007    78      3      0     .378  1.44   3.34   .635   .777   .282   2.58   .442   .063   2
  4 08JL202b 1933 2007    75      3      0     .412  2.07   5.55  1.150   .625   .315   2.64   .533   .103   3
  5 08JL203a 1926 2007    82      3      0     .520  2.12   6.00  1.023   .834   .190   2.55   .378  -.078   1
  6 08JL203b 1939 2007    69      3      0     .654  1.72   5.21  1.027   .892   .234   2.55   .468  -.046   1
  7 08JL204a 1843 2007   165      7      1     .433  1.04   3.19   .716   .882   .258   2.87   .434   .007   1
  8 08JL204b 1831 2007   177      7      3     .455   .91   2.71   .578   .850   .279   2.42   .260  -.039   1
  9 08JL205a 1929 2007    79      3      0     .505  1.80   5.35  1.049   .838   .231   2.64   .515  -.054   1
 10 08JL205b 1903 1996    94      3      0     .655  1.21   8.72   .926   .534   .248   2.81   .511   .027   1
 11 08JL206a 1909 2007    99      4      1     .504  2.28   8.24  1.748   .849   .327   2.63   .498   .052   1
 12 08JL206b 1903 2007   105      4      2     .372  2.26   8.71  1.985   .925   .287   2.65   .459   .010   1
 13 08JL207a 1920 2007    88      4      0     .601  2.01   7.71  1.611   .874   .255   2.78   .491  -.046   1
 14 08JL207b 1923 2007    85      4      0     .637  1.80   5.87  1.468   .904   .271   2.75   .595  -.010   1
 15 08JL208a 1910 2007    98      4      0     .472  1.20   4.47  1.056   .915   .271   2.82   .562  -.045   1
 16 08JL208b 1889 2003   115      5      1     .402  1.31   4.40  1.115   .871   .285   2.77   .485   .009   1
 17 08JL209a 1911 2007    97      4      0     .450  1.55   7.50  1.453   .880   .254   2.67   .480   .022   1
 18 08JL209b 1908 2007   100      4      3     .333  1.50   4.52  1.299   .904   .253   2.83   .490  -.033   1
--- -------- --------- -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
Total or mean:          1843     75     11     .478  1.59   8.72  1.148   .853   .262   2.87   .456  -.002

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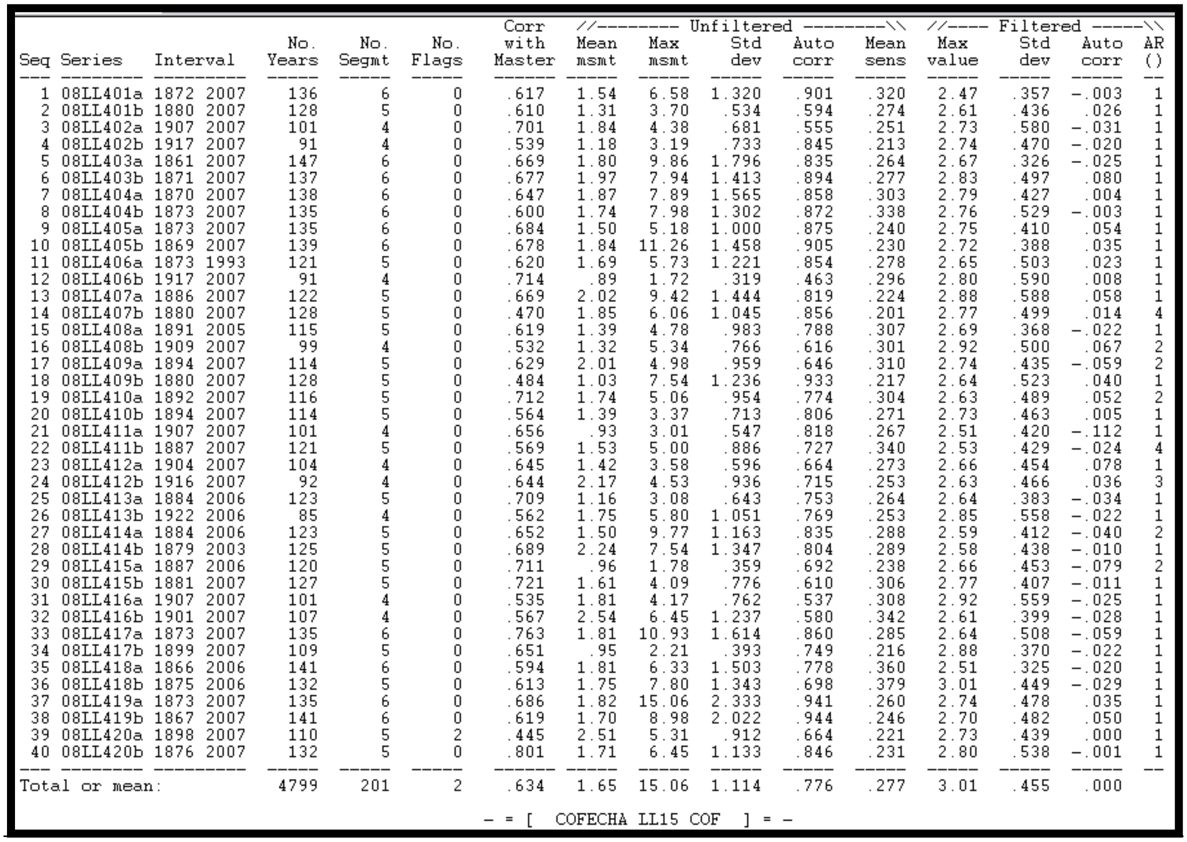
Cross-Dated White Pine Individual Site Chronologies

Private White (08LL400's)



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                                               Corr  //-------- Unfiltered --------\\  //---- Filtered -----\\
                         No.    No.    No.     with  Mean    Max    Std   Auto   Mean    Max    Std   Auto  AR
Seq Series   Interval  Years  Segmt  Flags   Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- --------- -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
  1 08LL401a 1872 2007   136      6      0     .617  1.54   6.58  1.320   .901   .320   2.47   .357  -.003   1
  2 08LL401b 1880 2007   128      5      0     .610  1.31   3.70   .534   .594   .274   2.61   .436   .026   1
  3 08LL402a 1907 2007   101      4      0     .701  1.84   4.38   .681   .555   .251   2.73   .580  -.031   1
  4 08LL402b 1917 2007    91      4      0     .539  1.18   3.19   .733   .845   .213   2.74   .470  -.020   1
  5 08LL403a 1861 2007   147      6      0     .669  1.80   9.86  1.796   .835   .264   2.67   .326  -.025   1
  6 08LL403b 1871 2007   137      6      0     .677  1.97   7.94  1.413   .894   .277   2.83   .497   .080   1
  7 08LL404a 1870 2007   138      6      0     .647  1.87   7.89  1.565   .858   .303   2.79   .427   .004   1
  8 08LL404b 1873 2007   135      6      0     .600  1.74   7.98  1.302   .872   .338   2.76   .529  -.003   1
  9 08LL405a 1873 2007   135      6      0     .684  1.50   5.18  1.000   .875   .240   2.75   .410   .054   1
 10 08LL405b 1869 2007   139      6      0     .678  1.84  11.26  1.458   .905   .230   2.72   .388   .035   1
 11 08LL406a 1873 1993   121      5      0     .620  1.69   5.73  1.221   .854   .278   2.65   .503   .023   1
 12 08LL406b 1917 2007    91      4      0     .714   .89   1.72   .319   .463   .296   2.80   .590   .008   1
 13 08LL407a 1886 2007   122      5      0     .669  2.02   9.42  1.444   .819   .224   2.88   .588   .058   1
 14 08LL407b 1880 2007   128      5      0     .470  1.85   6.06  1.045   .856   .201   2.77   .499   .014   4
 15 08LL408a 1891 2005   115      5      0     .619  1.39   4.78   .983   .788   .307   2.69   .368  -.022   1
 16 08LL408b 1909 2007    99      4      0     .532  1.32   5.34   .766   .616   .301   2.92   .500   .067   2
 17 08LL409a 1894 2007   114      5      0     .629  2.01   4.98   .959   .646   .310   2.74   .435  -.059   2
 18 08LL409b 1880 2007   128      5      0     .484  1.03   7.54  1.236   .933   .217   2.64   .523   .040   1
 19 08LL410a 1892 2007   116      5      0     .712  1.74   5.06   .954   .774   .304   2.63   .489   .052   2
 20 08LL410b 1894 2007   114      5      0     .564  1.39   3.37   .713   .806   .271   2.73   .463   .005   1
 21 08LL411a 1907 2007   101      4      0     .656   .93   3.01   .547   .818   .267   2.51   .420  -.112   1
 22 08LL411b 1887 2007   121      5      0     .569  1.53   5.00   .886   .727   .340   2.53   .429  -.024   4
 23 08LL412a 1904 2007   104      4      0     .645  1.42   3.58   .596   .664   .273   2.66   .454   .078   1
 24 08LL412b 1916 2007    92      4      0     .644  2.17   4.53   .936   .715   .253   2.63   .466   .036   3
 25 08LL413a 1884 2006   123      5      0     .709  1.16   3.08   .643   .753   .264   2.64   .383  -.034   1
 26 08LL413b 1922 2006    85      4      0     .562  1.75   5.80  1.051   .769   .253   2.85   .558  -.022   1
 27 08LL414a 1884 2006   123      5      0     .652  1.50   9.77  1.163   .835   .288   2.59   .412  -.040   2
 28 08LL414b 1879 2003   125      5      0     .689  2.24   7.54  1.347   .804   .289   2.58   .438  -.010   1
 29 08LL415a 1887 2006   120      5      0     .711   .96   1.78   .359   .692   .238   2.66   .453  -.079   2
 30 08LL415b 1881 2007   127      5      0     .721  1.61   4.09   .776   .610   .306   2.77   .407  -.011   1
 31 08LL416a 1907 2007   101      4      0     .535  1.81   4.17   .762   .537   .308   2.92   .559  -.025   1
 32 08LL416b 1901 2007   107      4      0     .567  2.54   6.45  1.237   .580   .342   2.61   .399  -.028   1
 33 08LL417a 1873 2007   135      6      0     .763  1.81  10.93  1.614   .860   .285   2.64   .508  -.059   1
 34 08LL417b 1899 2007   109      5      0     .651   .95   2.21   .393   .749   .216   2.88   .370  -.022   1
 35 08LL418a 1866 2006   141      6      0     .594  1.81   6.33  1.503   .778   .360   2.51   .325  -.020   1
 36 08LL418b 1875 2006   132      5      0     .613  1.75   7.80  1.343   .698   .379   3.01   .449  -.029   1
 37 08LL419a 1873 2007   135      6      0     .686  1.82  15.06  2.333   .941   .260   2.74   .478   .035   1
 38 08LL419b 1867 2007   141      6      0     .619  1.70   8.98  2.022   .944   .246   2.70   .482   .050   1
 39 08LL420a 1898 2007   110      5      2     .445  2.51   5.31   .912   .664   .221   2.73   .439   .000   1
 40 08LL420b 1876 2007   132      5      0     .801  1.71   6.45  1.133   .846   .231   2.80   .538  -.001   1
--- -------- --------- -----  -----  -----   ------ -----  -----  -----  -----  -----  -----  -----  -----  --
Total or mean:          4799    201      2     .634  1.65  15.06  1.114   .776   .277   3.01   .455   .000

                                              - = [  COFECHA LL15 COF  ] = -
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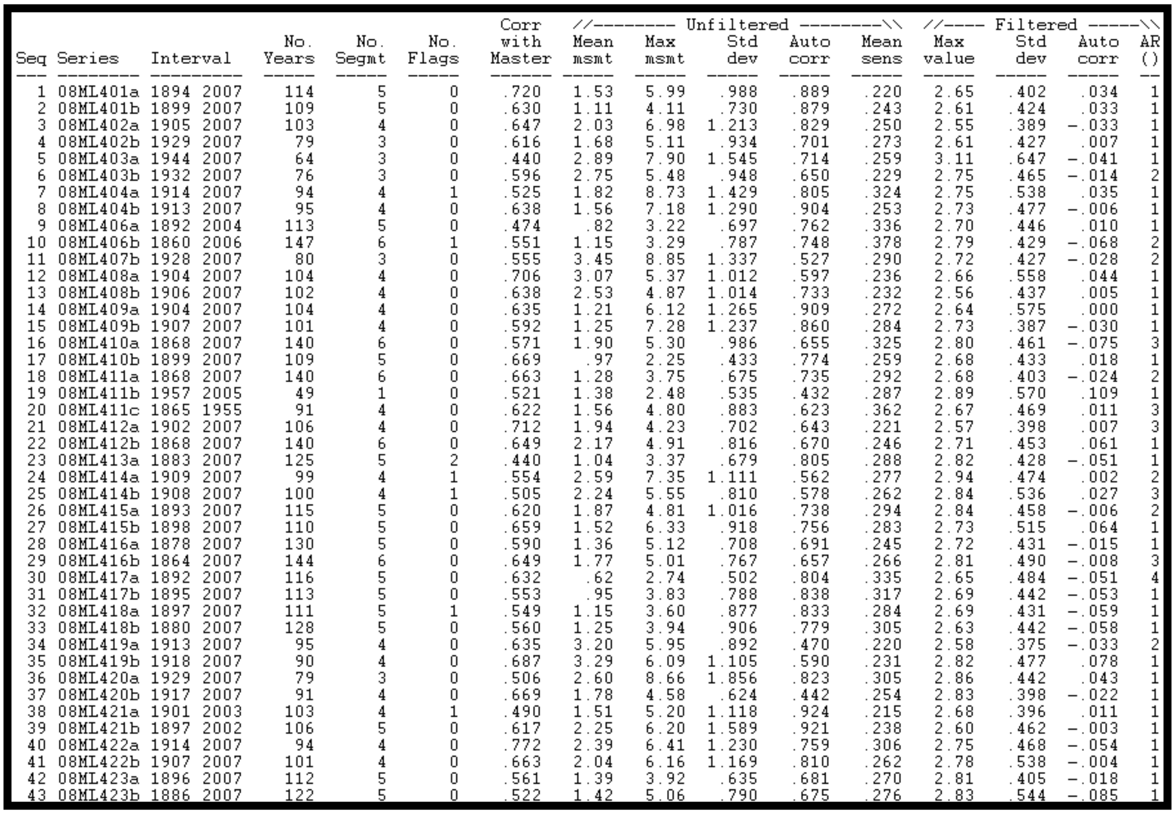
Griffen West (08ML400's)



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                                                 Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                                 No.    No.    No.    with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
Seq Series   Interval   Years  Segmt  Flags  Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- ---------  -----  -----  -----  ------ -----  -----  -----  -----  -----  -----  -----  -----  --
  1 08ML401a 1894 2007    114      5      0    .720  1.53   5.99   .988   .889   .220   2.65   .402   .034   1
  2 08ML401b 1899 2007    109      5      0    .630  1.11   4.11   .730   .879   .243   2.61   .424   .033   1
  3 08ML402a 1905 2007    103      4      0    .647  2.03   6.98  1.213   .829   .250   2.55   .389  -.033   1
  4 08ML402b 1929 2007     79      3      0    .616  1.68   5.11   .934   .701   .273   2.61   .427   .007   1
  5 08ML403a 1944 2007     64      3      0    .440  2.89   7.90  1.545   .714   .259   3.11   .647  -.041   1
  6 08ML403b 1932 2007     76      3      0    .596  2.75   5.48   .948   .650   .229   2.75   .465  -.014   2
  7 08ML404a 1914 2007     94      4      1    .525  1.82   8.73  1.429   .805   .324   2.75   .538   .035   1
  8 08ML404b 1913 2007     95      4      0    .638  1.56   7.18  1.290   .904   .253   2.73   .477  -.006   1
  9 08ML406a 1892 2004    113      5      0    .474   .82   3.22   .697   .762   .336   2.70   .446   .010   1
 10 08ML406b 1860 2006    147      6      1    .551  1.15   3.29   .787   .748   .378   2.79   .429  -.068   2
 11 08ML407b 1928 2007     80      3      0    .555  3.45   8.85  1.337   .527   .290   2.72   .427  -.028   2
 12 08ML408a 1904 2007    104      4      0    .706  3.07   5.37  1.012   .597   .236   2.66   .558   .044   1
 13 08ML408b 1906 2007    102      4      0    .638  2.53   4.87  1.014   .733   .232   2.56   .437   .005   1
 14 08ML409a 1904 2007    104      4      0    .635  1.21   6.12  1.265   .909   .272   2.64   .575   .000   1
 15 08ML409b 1907 2007    101      4      0    .592  1.25   7.28  1.237   .860   .284   2.73   .387  -.030   1
 16 08ML410a 1868 2007    140      6      0    .571  1.90   5.30   .986   .655   .325   2.80   .461  -.075   3
 17 08ML410b 1899 2007    109      5      0    .669   .97   2.25   .433   .774   .259   2.68   .433   .018   1
 18 08ML411a 1868 2007    140      6      0    .663  1.28   3.75   .675   .735   .292   2.68   .403  -.024   2
 19 08ML411b 1957 2005     49      1      0    .521  1.38   2.48   .535   .432   .287   2.89   .570   .109   1
 20 08ML411c 1865 1955     91      4      0    .622  1.56   4.80   .883   .623   .362   2.67   .469   .011   3
 21 08ML412a 1902 2007    106      4      0    .712  1.94   4.23   .702   .643   .221   2.57   .398   .007   3
 22 08ML412b 1868 2007    140      6      0    .649  2.17   4.91   .816   .670   .246   2.71   .453   .061   1
 23 08ML413a 1883 2007    125      5      2    .440  1.04   3.37   .679   .805   .288   2.82   .428  -.051   1
 24 08ML414a 1909 2007     99      4      1    .554  2.59   7.35  1.111   .562   .277   2.94   .474   .002   2
 25 08ML414b 1908 2007    100      4      1    .505  2.24   5.55   .810   .578   .262   2.84   .536   .027   3
 26 08ML415a 1893 2007    115      5      0    .620  1.87   4.81  1.016   .738   .294   2.84   .458  -.006   2
 27 08ML415b 1898 2007    110      5      0    .659  1.52   6.33   .918   .756   .283   2.73   .515   .064   1
 28 08ML416a 1878 2007    130      5      0    .590  1.36   5.12   .708   .691   .245   2.72   .431  -.015   1
 29 08ML416b 1864 2007    144      6      0    .649  1.77   5.01   .767   .657   .266   2.81   .490  -.008   3
 30 08ML417a 1892 2007    116      5      0    .632   .62   2.74   .502   .804   .335   2.65   .484  -.051   4
 31 08ML417b 1895 2007    113      5      0    .553   .95   3.83   .788   .838   .317   2.69   .442  -.053   1
 32 08ML418a 1897 2007    111      5      1    .549  1.15   3.60   .877   .833   .284   2.69   .431  -.059   1
 33 08ML418b 1880 2007    128      5      0    .560  1.25   3.94   .906   .779   .305   2.63   .442  -.058   1
 34 08ML419a 1913 2007     95      4      0    .635  3.20   5.95   .892   .470   .220   2.58   .375  -.033   2
 35 08ML419b 1918 2007     90      4      0    .687  3.29   6.09  1.105   .590   .231   2.82   .477   .078   1
 36 08ML420a 1929 2007     79      3      0    .506  2.60   8.66  1.856   .823   .305   2.86   .442   .043   1
 37 08ML420b 1917 2007     91      4      0    .669  1.78   4.58   .624   .442   .254   2.83   .398  -.022   1
 38 08ML421a 1901 2003    103      4      1    .490  1.51   5.20  1.118   .924   .215   2.68   .396   .011   1
 39 08ML421b 1897 2002    106      5      0    .617  2.25   6.20  1.589   .921   .238   2.60   .462  -.003   1
 40 08ML422a 1914 2007     94      4      0    .772  2.39   6.41  1.230   .759   .306   2.75   .468  -.054   1
 41 08ML422b 1907 2007    101      4      0    .663  2.04   6.16  1.169   .810   .262   2.78   .538  -.004   1
 42 08ML423a 1896 2007    112      5      0    .561  1.39   3.92   .635   .681   .270   2.81   .405  -.018   1
 43 08ML423b 1886 2007    122      5      0    .522  1.42   5.06   .790   .675   .276   2.83   .544  -.085   1
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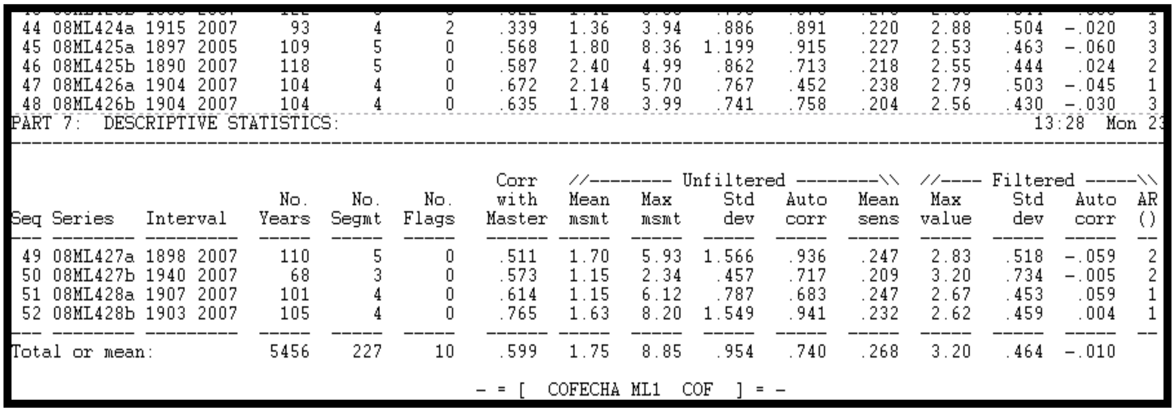

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 44 08ML424a 1915 2007     93      4      2    .339  1.36   3.94   .886   .891   .220   2.88   .504  -.020   3
 45 08ML425a 1897 2005    109      5      0    .568  1.80   8.36  1.199   .915   .227   2.53   .463  -.060   3
 46 08ML425b 1890 2007    118      5      0    .587  2.40   4.99   .862   .713   .218   2.55   .444   .024   2
 47 08ML426a 1904 2007    104      4      0    .672  2.14   5.70   .767   .452   .238   2.79   .503  -.045   1
 48 08ML426b 1904 2007    104      4      0    .635  1.78   3.99   .741   .758   .204   2.56   .430  -.030   3
PART 7:  DESCRIPTIVE STATISTICS:                                                                13:28  Mon 23
------------------------------------------------------------------------------------------------------------------

                                                 Corr   //-------- Unfiltered --------\\  //---- Filtered -----\\
                                 No.    No.    No.    with   Mean   Max     Std   Auto   Mean   Max     Std   Auto  AR
Seq Series   Interval   Years  Segmt  Flags  Master  msmt   msmt    dev   corr   sens  value    dev   corr  ()
--- -------- ---------  -----  -----  -----  ------ -----  -----  -----  -----  -----  -----  -----  -----  --
 49 08ML427a 1898 2007    110      5      0    .511  1.70   5.93  1.566   .936   .247   2.83   .518  -.059   2
 50 08ML427b 1940 2007     68      3      0    .573  1.15   2.34   .457   .717   .209   3.20   .734  -.005   2
 51 08ML428a 1907 2007    101      4      0    .614  1.15   6.12   .787   .683   .247   2.67   .453   .059   1
 52 08ML428b 1903 2007    105      4      0    .765  1.63   8.20  1.549   .941   .232   2.62   .459   .004   1
--- -------- ---------  -----  -----  -----  ------ -----  -----  -----  -----  -----  -----  -----  -----  --
Total or mean:           5456    227     10    .599  1.75   8.85   .954   .740   .268   3.20   .464  -.010

                                  - = [  COFECHA ML1  COF  ] = -
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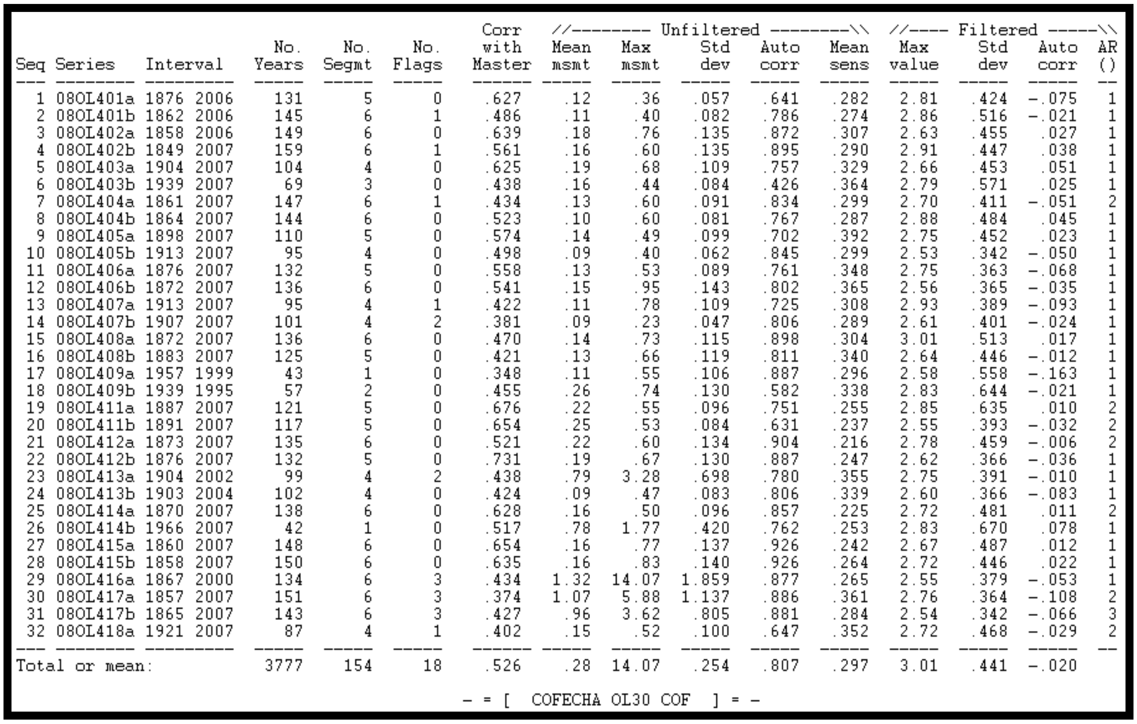
Indian Woods (08OL400’s)



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                                            Corr  //-------- Unfiltered --------\\  //---- Filtered -----\\
                         No.   No.   No.    with  Mean   Max   Std  Auto  Mean   Max   Std  Auto  AR
Seq Series   Interval  Years Segmt Flags  Master  msmt  msmt   dev  corr  sens value   dev  corr  ()
--- -------- --------- ----- ----- -----  ------ ----- ----- ----- ----- ----- ----- ----- -----  --
  1 08OL401a 1876 2006   131     5     0    .627   .12   .36  .057  .641  .282  2.81  .424 -.075   1
  2 08OL401b 1862 2006   145     6     1    .486   .11   .40  .082  .786  .274  2.86  .516 -.021   1
  3 08OL402a 1858 2006   149     6     0    .639   .18   .76  .135  .872  .307  2.63  .455  .027   1
  4 08OL402b 1849 2007   159     6     1    .561   .16   .60  .135  .895  .290  2.91  .447  .038   1
  5 08OL403a 1904 2007   104     4     0    .625   .19   .68  .109  .757  .329  2.66  .453  .051   1
  6 08OL403b 1939 2007    69     3     0    .438   .16   .44  .084  .426  .364  2.79  .571  .025   1
  7 08OL404a 1861 2007   147     6     1    .434   .13   .60  .091  .834  .299  2.70  .411 -.051   2
  8 08OL404b 1864 2007   144     6     0    .523   .10   .60  .081  .767  .287  2.88  .484  .045   1
  9 08OL405a 1898 2007   110     5     0    .574   .14   .49  .099  .702  .392  2.75  .452  .023   1
 10 08OL405b 1913 2007    95     4     0    .498   .09   .40  .062  .845  .299  2.53  .342 -.050   1
 11 08OL406a 1876 2007   132     5     0    .558   .13   .53  .089  .761  .348  2.75  .363 -.068   1
 12 08OL406b 1872 2007   136     6     0    .541   .15   .95  .143  .802  .365  2.56  .365 -.035   1
 13 08OL407a 1913 2007    95     4     1    .422   .11   .78  .109  .725  .308  2.93  .389 -.093   1
 14 08OL407b 1907 2007   101     4     2    .381   .09   .23  .047  .806  .289  2.61  .401 -.024   1
 15 08OL408a 1872 2007   136     6     0    .470   .14   .73  .115  .898  .304  3.01  .513  .017   1
 16 08OL408b 1883 2007   125     5     0    .421   .13   .66  .119  .811  .340  2.64  .446 -.012   1
 17 08OL409a 1957 1999    43     1     0    .348   .11   .55  .106  .887  .296  2.58  .558 -.163   1
 18 08OL409b 1939 1995    57     2     0    .455   .26   .74  .130  .582  .338  2.83  .644 -.021   1
 19 08OL411a 1887 2007   121     5     0    .676   .22   .55  .096  .751  .255  2.85  .635  .010   2
 20 08OL411b 1891 2007   117     5     0    .654   .25   .53  .084  .631  .237  2.55  .393 -.032   2
 21 08OL412a 1873 2007   135     6     0    .521   .22   .60  .134  .904  .216  2.78  .459 -.006   2
 22 08OL412b 1876 2007   132     5     0    .731   .19   .67  .130  .887  .247  2.62  .366 -.036   1
 23 08OL413a 1904 2002    99     4     2    .438   .79  3.28  .698  .780  .355  2.75  .391 -.010   1
 24 08OL413b 1903 2004   102     4     0    .424   .09   .47  .083  .806  .339  2.60  .366 -.083   1
 25 08OL414a 1870 2007   138     6     0    .628   .16   .50  .096  .857  .225  2.72  .481  .011   2
 26 08OL414b 1966 2007    42     1     0    .517   .78  1.77  .420  .762  .253  2.83  .670  .078   1
 27 08OL415a 1860 2007   148     6     0    .654   .16   .77  .137  .926  .242  2.67  .487  .012   1
 28 08OL415b 1858 2007   150     6     0    .635   .16   .83  .140  .926  .264  2.72  .446  .022   1
 29 08OL416a 1867 2000   134     6     3    .434  1.32 14.07 1.859  .877  .265  2.55  .379 -.053   1
 30 08OL417a 1857 2007   151     6     3    .374  1.07  5.88 1.137  .886  .361  2.76  .364 -.108   2
 31 08OL417b 1865 2007   143     6     3    .427   .96  3.62  .805  .881  .284  2.54  .342 -.066   3
 32 08OL418a 1921 2007    87     4     1    .402   .15   .52  .100  .647  .352  2.72  .468 -.029   2
--- -------- --------- ----- ----- -----  ------ ----- ----- ----- ----- ----- ----- ----- -----  --
Total or mean:          3777   154    18    .526   .28 14.07  .254  .807  .297  3.01  .441 -.020

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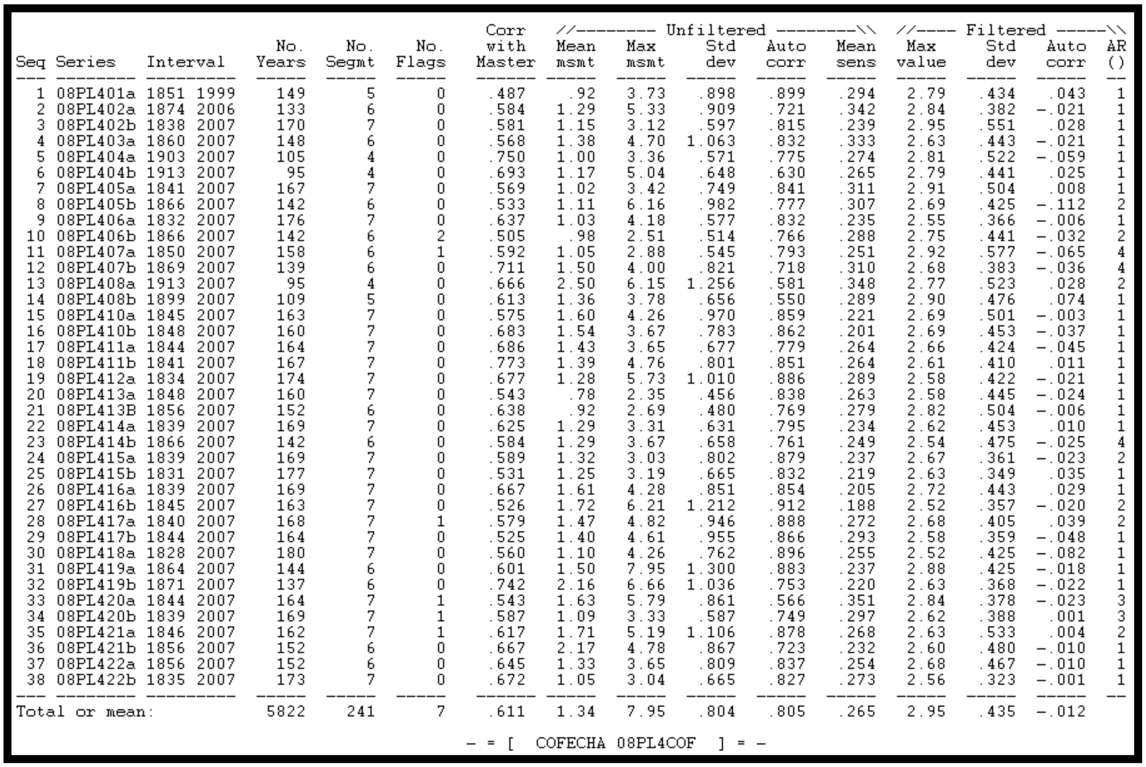
Homer Watson (08PL400’s)



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                                            Corr  //-------- Unfiltered --------\\  //---- Filtered -----\\
                         No.   No.   No.    with  Mean   Max   Std  Auto  Mean   Max   Std  Auto  AR
Seq Series   Interval  Years Segmt Flags  Master  msmt  msmt   dev  corr  sens value   dev  corr  ()
--- -------- --------- ----- ----- -----  ------ ----- ----- ----- ----- ----- ----- ----- -----  --
  1 08PL401a 1851 1999   149     5     0    .487   .92  3.73  .898  .899  .294  2.79  .434  .043   1
  2 08PL402a 1874 2006   133     6     0    .584  1.29  5.33  .909  .721  .342  2.84  .382 -.021   1
  3 08PL402b 1838 2007   170     7     0    .581  1.15  3.12  .597  .815  .239  2.95  .551  .028   1
  4 08PL403a 1860 2007   148     6     0    .568  1.38  4.70 1.063  .832  .333  2.63  .443 -.021   1
  5 08PL404a 1903 2007   105     4     0    .750  1.00  3.36  .571  .775  .274  2.81  .522 -.059   1
  6 08PL404b 1913 2007    95     4     0    .693  1.17  5.04  .648  .630  .265  2.79  .441  .025   1
  7 08PL405a 1841 2007   167     7     0    .569  1.02  3.42  .749  .841  .311  2.91  .504  .008   1
  8 08PL405b 1866 2007   142     6     0    .533  1.11  6.16  .982  .777  .307  2.69  .425 -.112   2
  9 08PL406a 1832 2007   176     7     0    .637  1.03  4.18  .577  .832  .235  2.55  .366 -.006   1
 10 08PL406b 1866 2007   142     6     2    .505   .98  2.51  .514  .766  .288  2.75  .441 -.032   2
 11 08PL407a 1850 2007   158     6     1    .592  1.05  2.88  .545  .793  .251  2.92  .577 -.065   4
 12 08PL407b 1869 2007   139     6     0    .711  1.50  4.00  .821  .718  .310  2.68  .383 -.036   4
 13 08PL408a 1913 2007    95     4     0    .666  2.50  6.15 1.256  .581  .348  2.77  .523  .028   2
 14 08PL408b 1899 2007   109     5     0    .613  1.36  3.78  .656  .550  .289  2.90  .476  .074   1
 15 08PL410a 1845 2007   163     7     0    .575  1.60  4.26  .970  .859  .221  2.69  .501 -.003   1
 16 08PL410b 1848 2007   160     7     0    .683  1.54  3.67  .783  .862  .201  2.69  .453 -.037   1
 17 08PL411a 1844 2007   164     7     0    .686  1.43  3.65  .677  .779  .264  2.66  .424 -.045   1
 18 08PL411b 1841 2007   167     7     0    .773  1.39  4.76  .801  .851  .264  2.61  .410  .011   1
 19 08PL412a 1834 2007   174     7     0    .677  1.28  5.73 1.010  .886  .289  2.58  .422 -.021   1
 20 08PL413a 1848 2007   160     7     0    .543   .78  2.35  .456  .838  .263  2.58  .445 -.024   1
 21 08PL413B 1856 2007   152     6     0    .638   .92  2.69  .480  .769  .279  2.82  .504 -.006   1
 22 08PL414a 1839 2007   169     7     0    .625  1.29  3.31  .631  .795  .234  2.62  .453  .010   1
 23 08PL414b 1866 2007   142     6     0    .584  1.29  3.67  .658  .761  .249  2.54  .475 -.025   4
 24 08PL415a 1839 2007   169     7     0    .589  1.32  3.03  .802  .879  .237  2.67  .361 -.023   2
 25 08PL415b 1831 2007   177     7     0    .531  1.25  3.19  .665  .832  .219  2.63  .349  .035   1
 26 08PL416a 1839 2007   169     7     0    .667  1.61  4.28  .851  .854  .205  2.72  .443  .029   1
 27 08PL416b 1845 2007   163     7     0    .526  1.72  6.21 1.212  .912  .188  2.52  .357 -.020   2
 28 08PL417a 1840 2007   168     7     1    .579  1.47  4.82  .946  .888  .272  2.68  .405  .039   2
 29 08PL417b 1844 2007   164     7     0    .525  1.40  4.61  .955  .866  .293  2.58  .359 -.048   1
 30 08PL418a 1828 2007   180     7     0    .560  1.10  4.26  .762  .896  .255  2.52  .425 -.082   1
 31 08PL419a 1864 2007   144     6     0    .601  1.50  7.95 1.300  .883  .237  2.88  .425 -.018   1
 32 08PL419b 1871 2007   137     6     0    .742  2.16  6.66 1.036  .753  .220  2.63  .368 -.022   1
 33 08PL420a 1844 2007   164     7     1    .543  1.63  5.79  .861  .566  .351  2.84  .378 -.023   3
 34 08PL420b 1839 2007   169     7     1    .587  1.09  3.33  .587  .749  .297  2.62  .388  .001   3
 35 08PL421a 1846 2007   162     7     1    .617  1.71  5.19 1.106  .878  .268  2.63  .533  .004   2
 36 08PL421b 1856 2007   152     6     0    .667  2.17  4.78  .867  .723  .232  2.60  .480 -.010   1
 37 08PL422a 1856 2007   152     6     0    .645  1.33  3.65  .809  .837  .254  2.68  .467 -.010   1
 38 08PL422b 1835 2007   173     7     0    .672  1.05  3.04  .665  .827  .273  2.56  .323 -.001   1
--- -------- --------- ----- ----- -----  ------ ----- ----- ----- ----- ----- ----- ----- -----  --
Total or mean:          5822   241     7    .611  1.34  7.95  .804  .805  .265  2.95  .435 -.012

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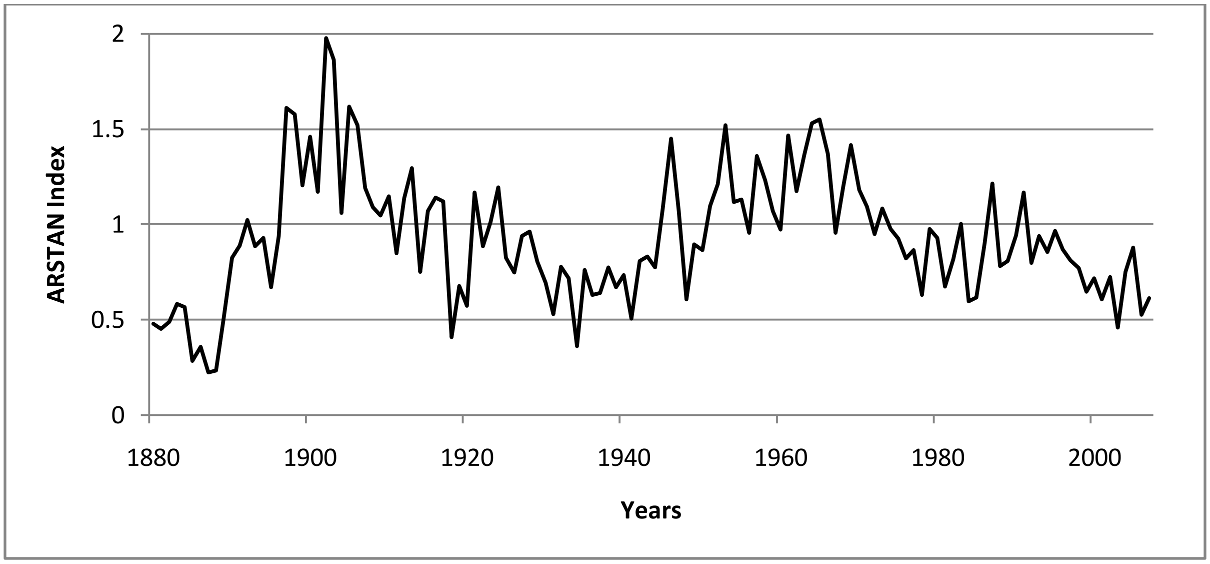
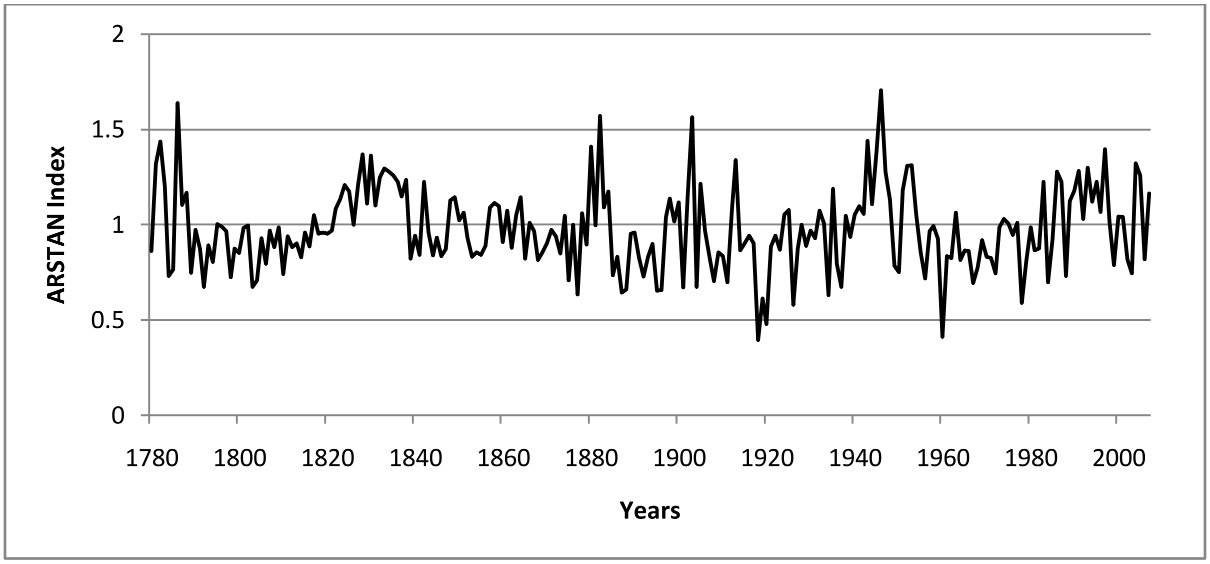
Appendix B

Standardized Eastern Hemlock Individual Site Chronologies

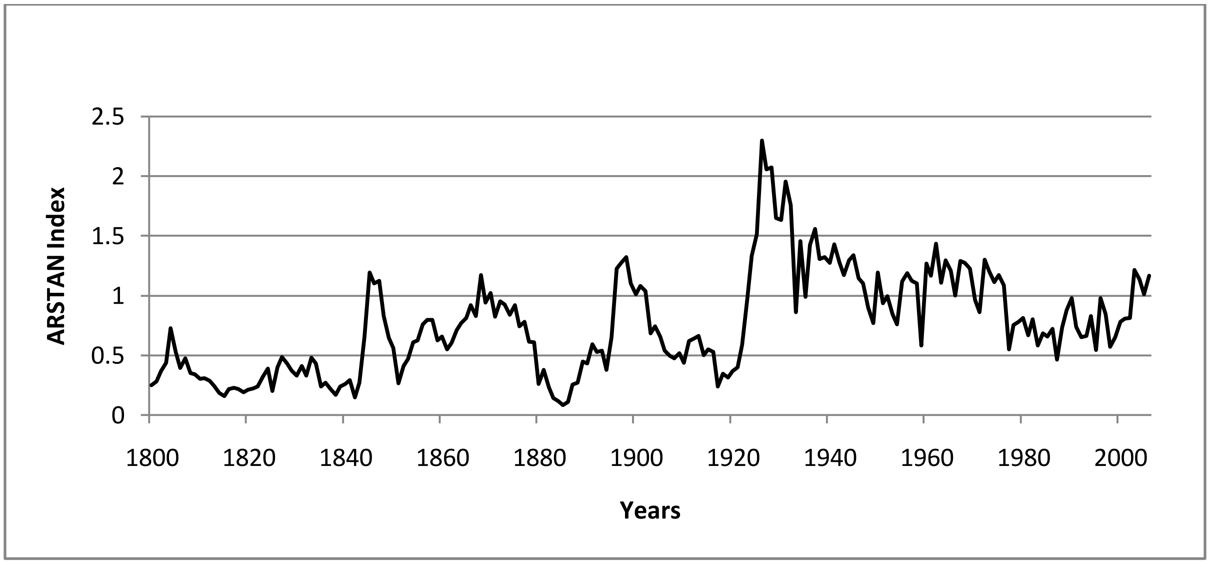
Luther Marsh (08IL800's)



Homer Watson (08PL800's)

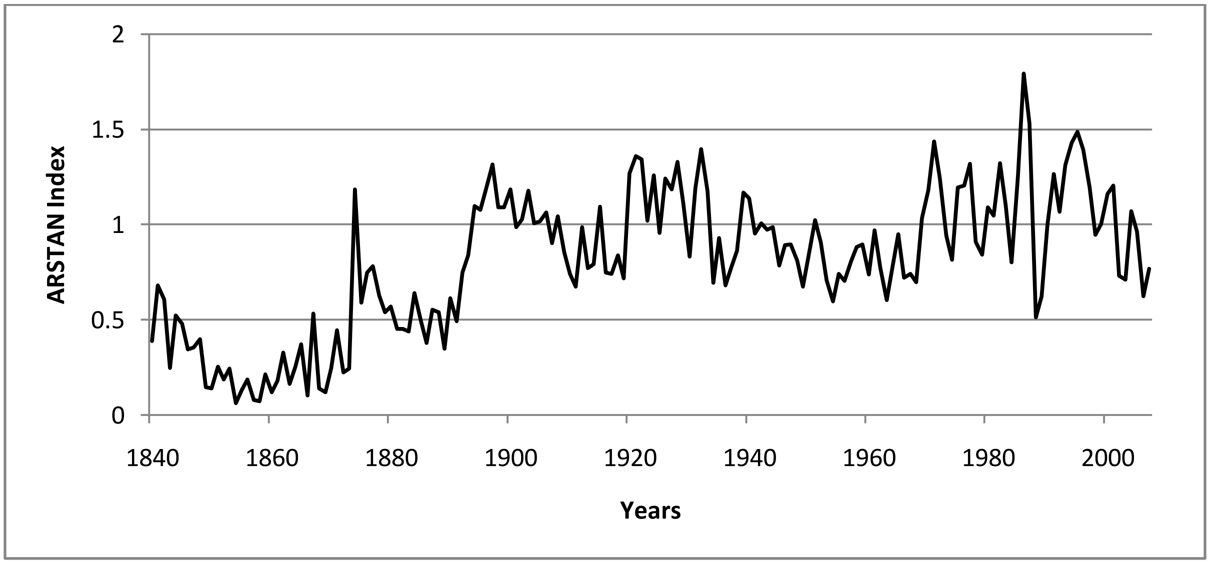


Oakland Swamp (08NL800's)

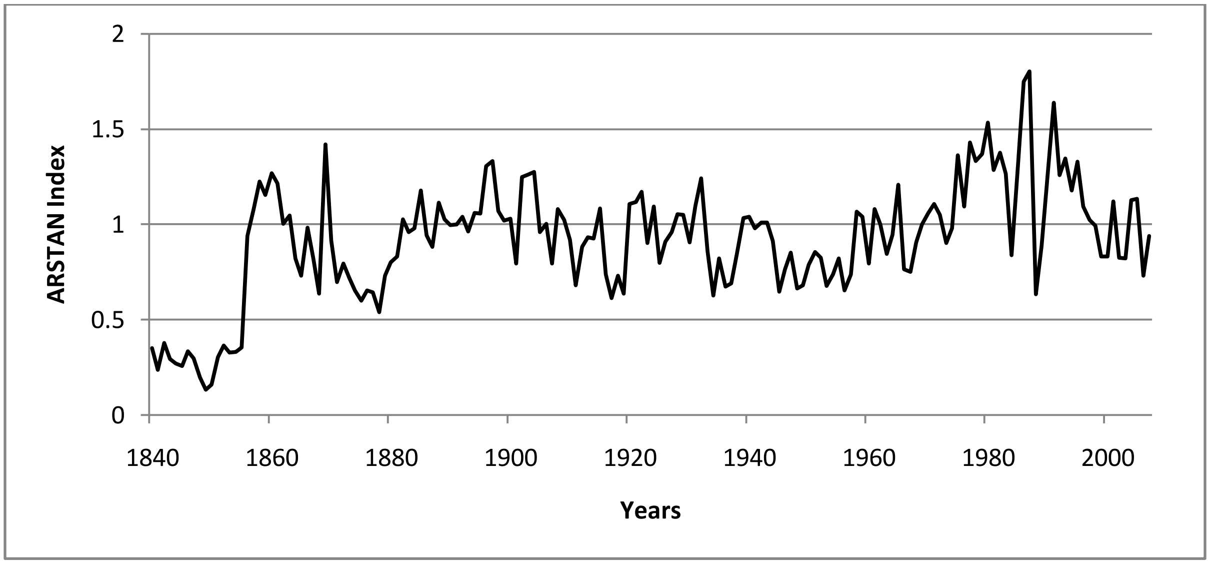


Standardized Sugar Maple Individual Site Chronologies

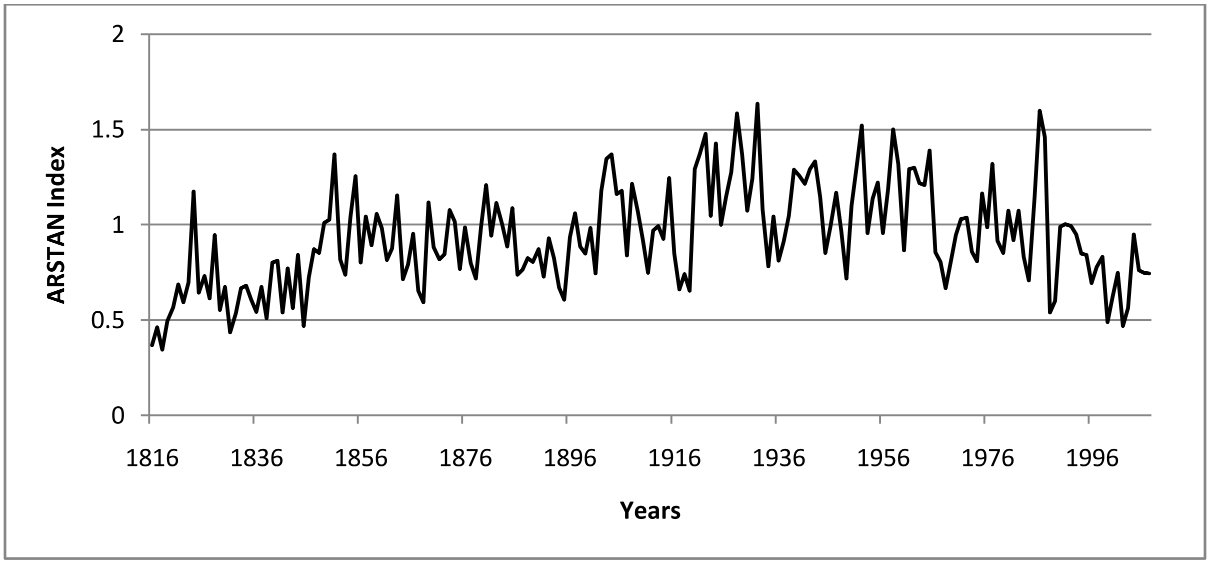
Guelph Lake (08KLE00's)



Indian Woods (08OLE00's)

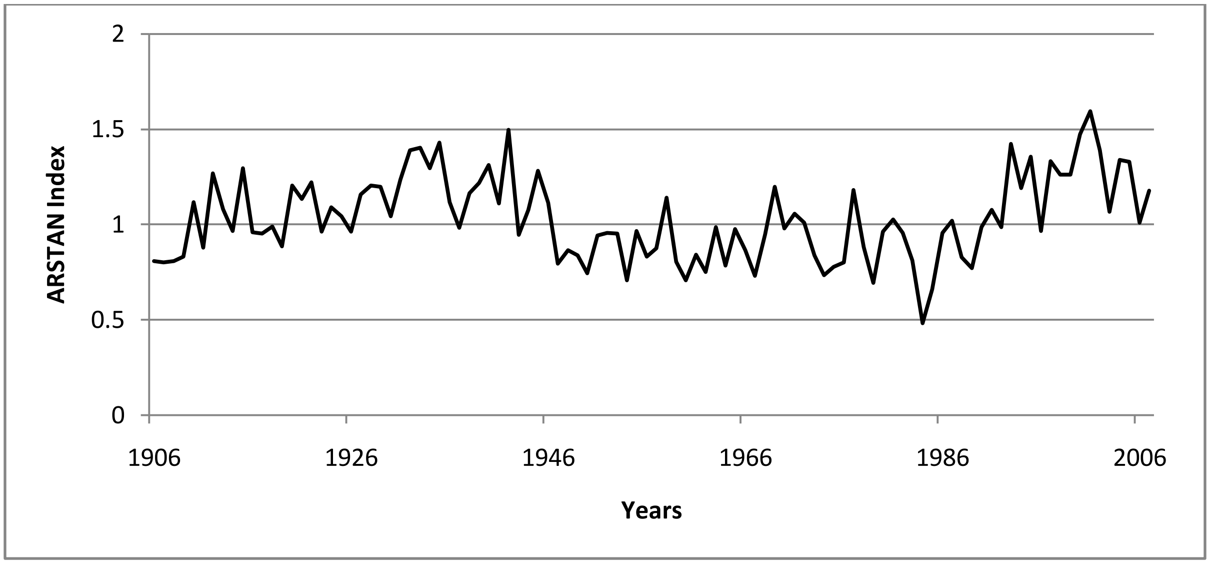


Homer Watson (08PLE00's)



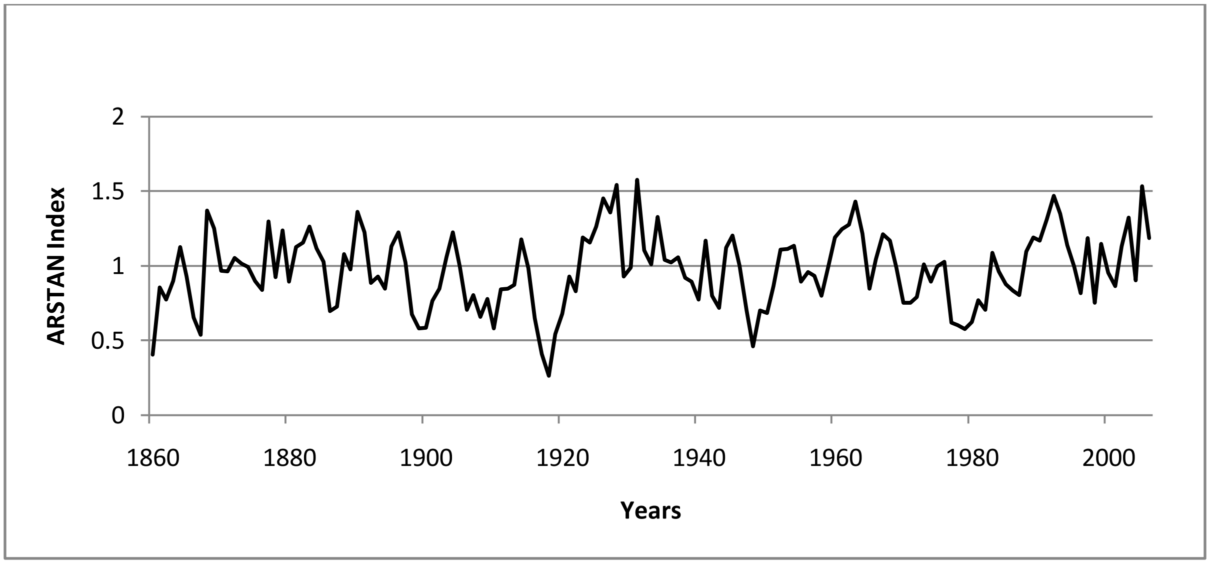
Standardized White Spruce Individual Site Chronology

Eramosa River (08JL200's)

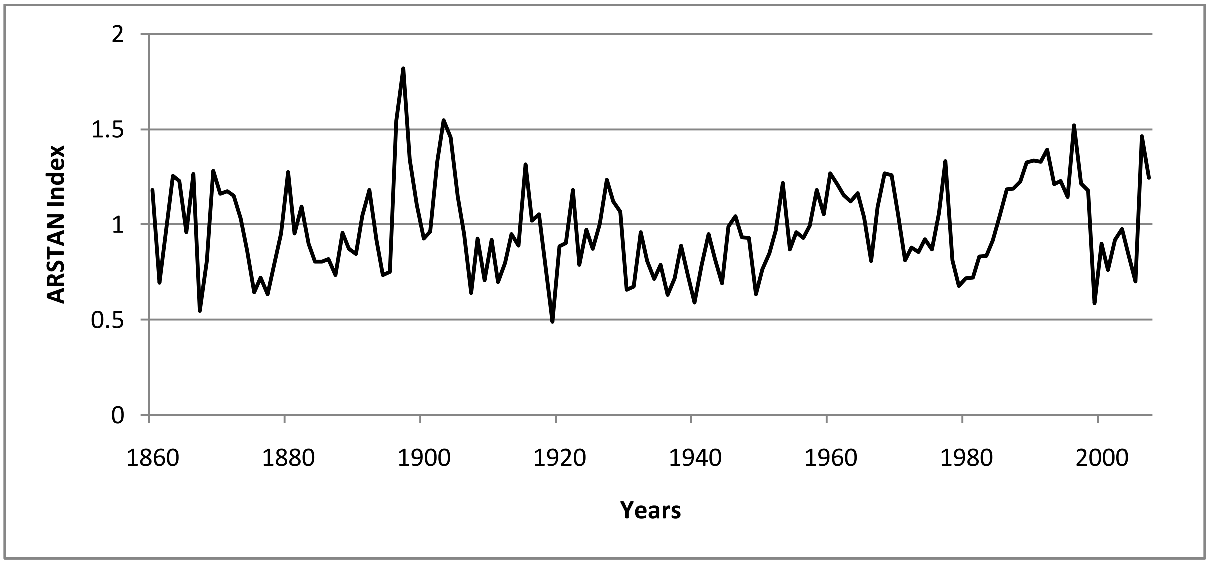


Standardized White Pine Individual Site Chronologies

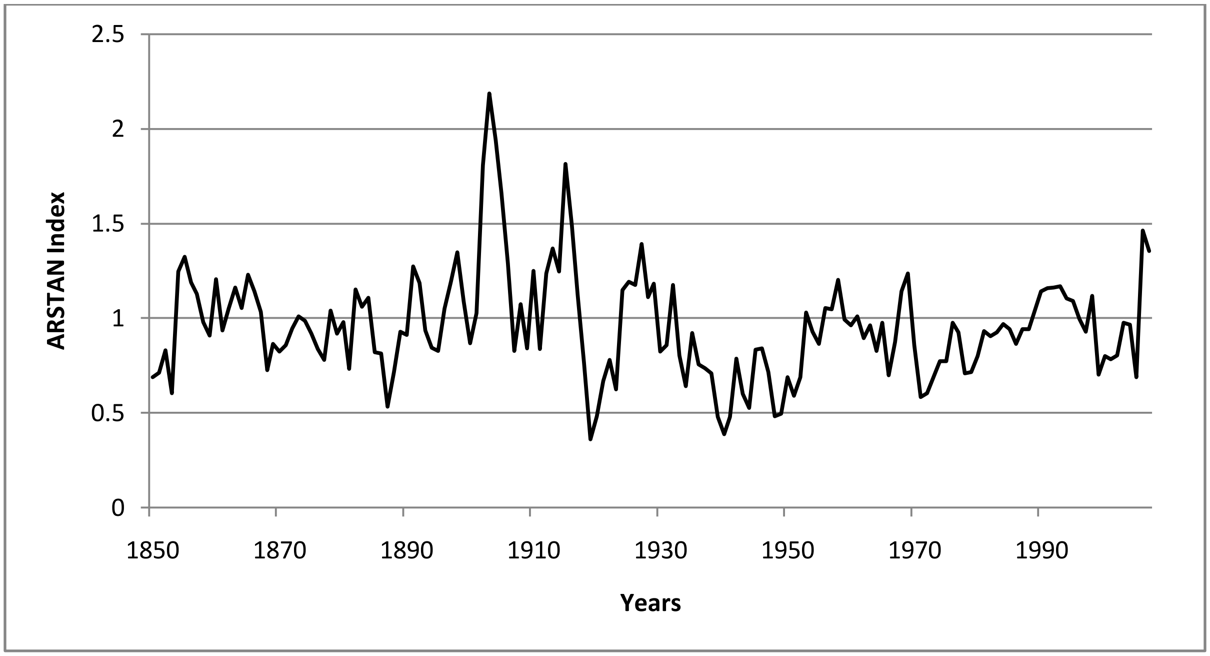
Private White (08LL400's)



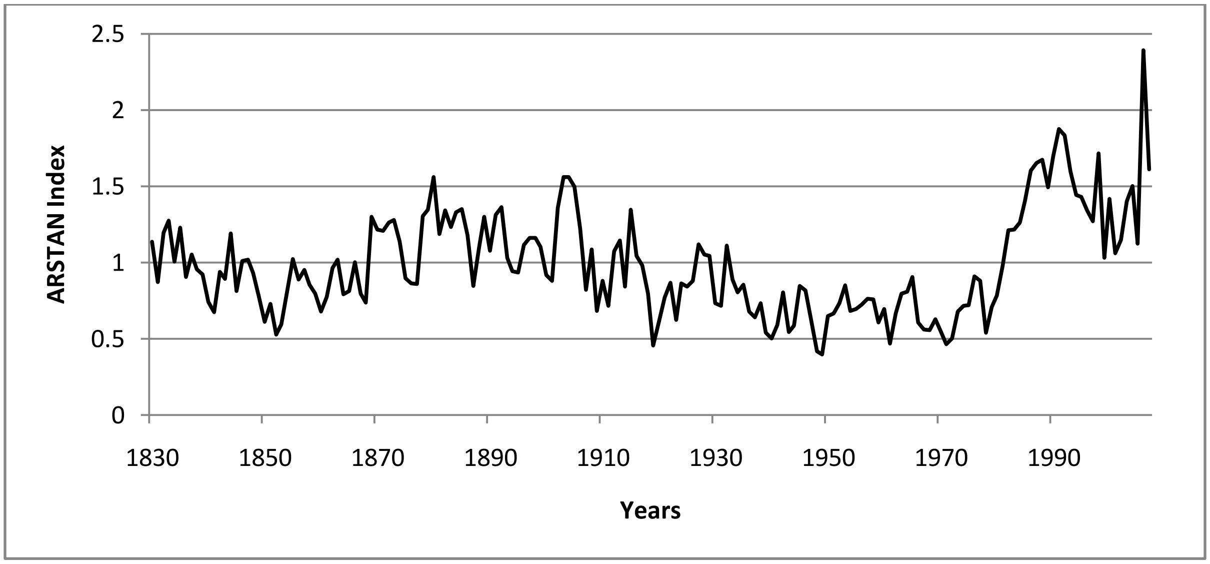
Griffen West (08ML400's)



Indian Woods (08OL400's)



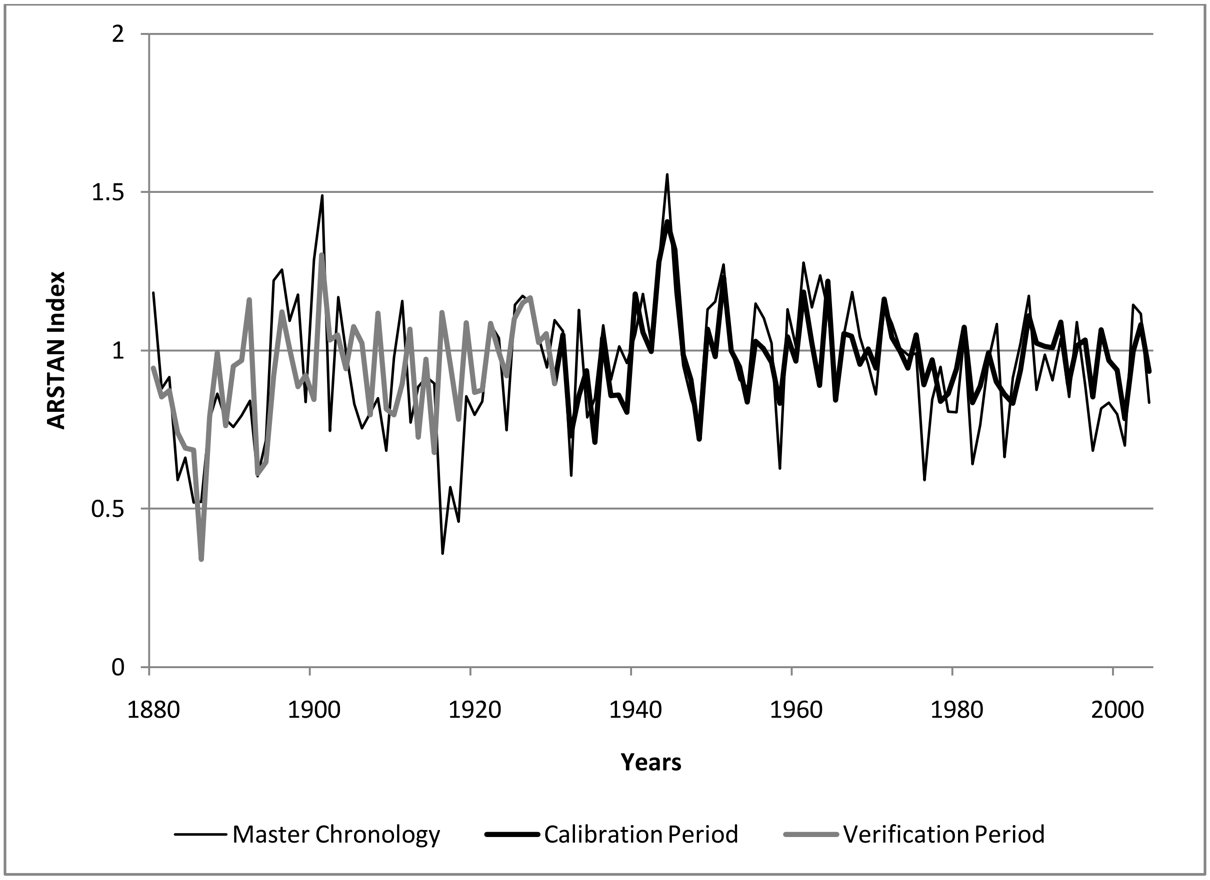
Homer Watson (08PL400’s)



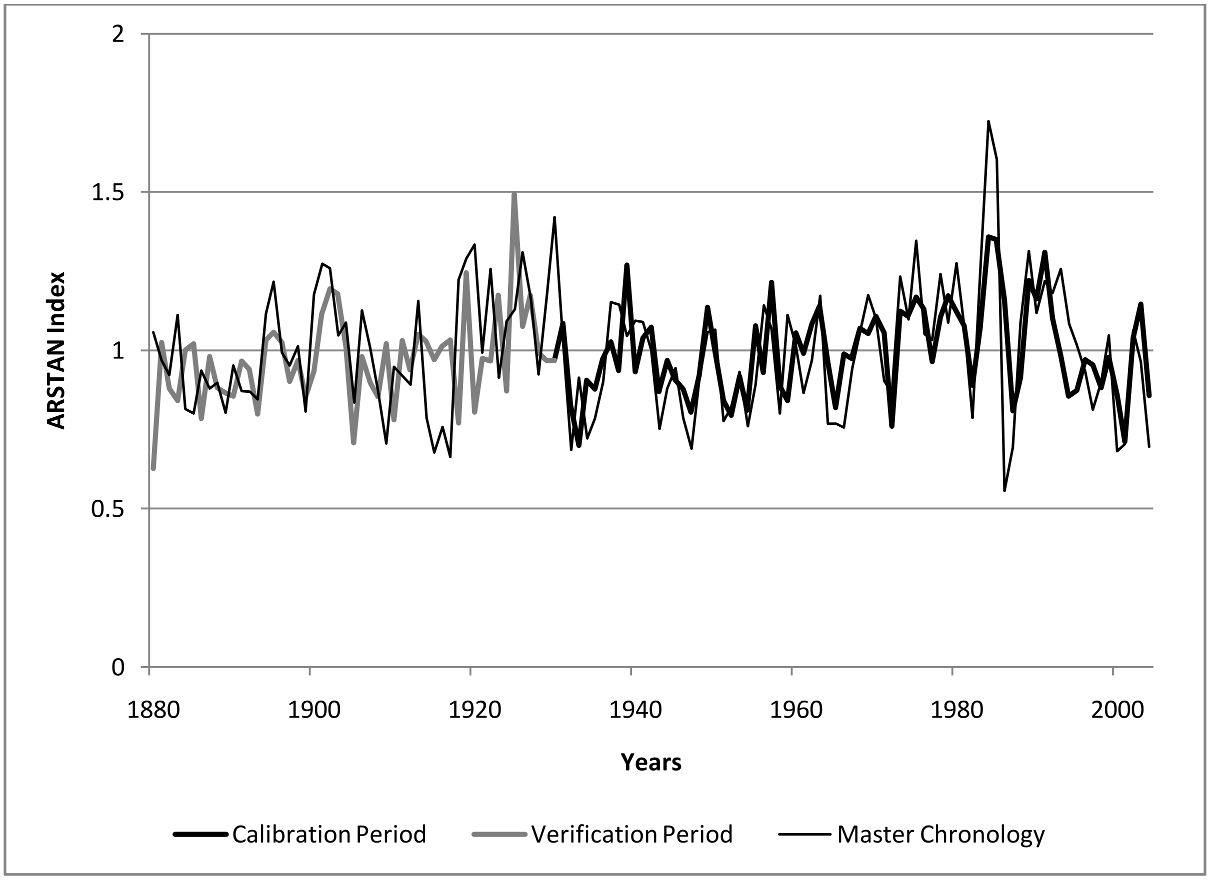
Appendix C

Calibration / Verification Visual Tests

Eastern Hemlock

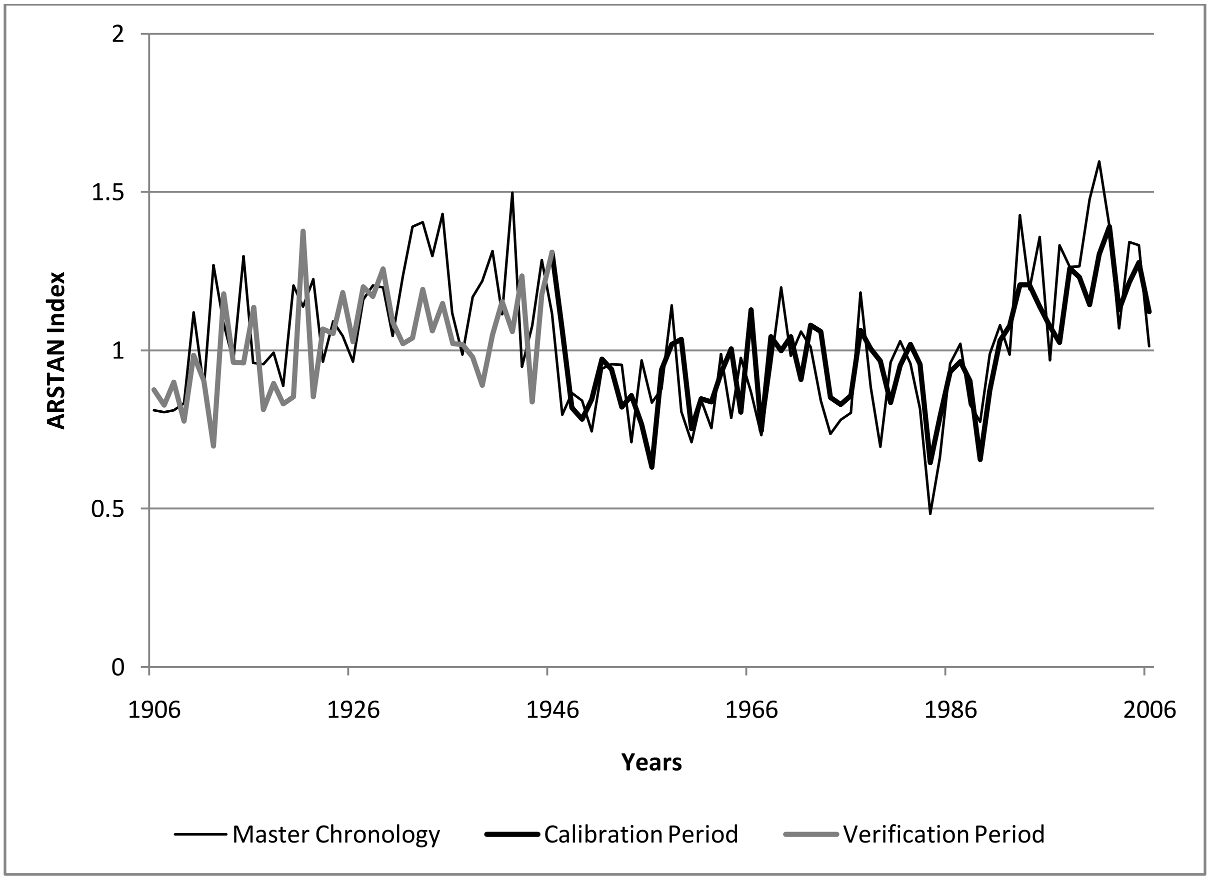


Sugar Maple

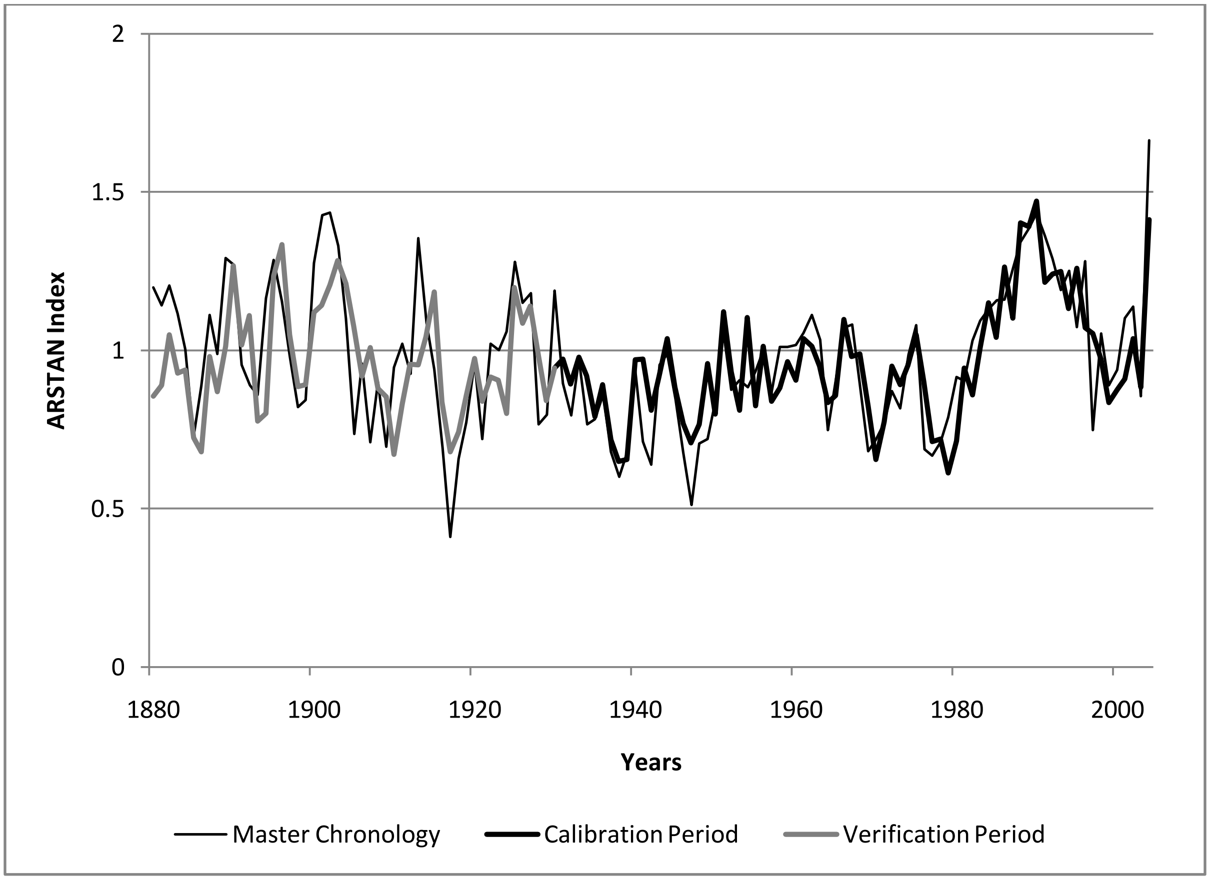


2
1.5
1
0.5
0
ARSTAN Index
1880
1900
1920
1940
1960
1980
2000
Years
Calibration Period
Verification Period
Master Chronology

White Spruce



White Pine



ARSTAN Index
2
1.5
1
0.5
0
1880
1900
1920
1940
1960
1980
2000
Years
Master Chronology
Calibration Period
Verification Period

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