

DENDROCHRONOLOGY IN THE CANADIAN PRARIES:  
EVALUATING THE USEFULNESS OF SHELTERBELT SPECIES  
NOW AND IN THE FUTURE

BY

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## **Abstract**

In the summer of 2012, students from the Mount Allison Dendrochronology Lab (MAD Lab) visited Saskatoon, Saskatchewan to complete fieldwork as a part of a four-year research program in association with the University of Saskatchewan and the Agricultural Greenhouse Gas Project. Shelterbelts, which include trees and shrubs planted around farmsteads and crops, were the subject of the research, and this thesis describes an effort to determine the carbon sequestration capacity of the nine of the most commonly planted shelterbelt species in the Canadian Prairies.

The analysis and results contained within this thesis represent the data collected in May 2011. Chapter I, “Evaluating the suitability of nine shelterbelt species for dendrochronological purposes in the Canadian Prairies”, is a manuscript submitted for publication. This manuscript details the initial creation of nine master chronologies for the Saskatoon area, and strives to determine the usefulness of each of the species for dendrochronological purposes. Chapter II, “Radial-growth Forecasting: the projected status of nine shelterbelt species in 2100”, uses Canadian Global Circulation Model data to forecast the likely growth patterns of shelterbelt species under three different climate scenarios. The results of this analysis will serve as an indicator to farmers landowners, informing their decision of which trees to plant in the present based on their ability to grow successfully and sequester carbon in the future.

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## **Statement of Co-authorship**

All data analysis was completed by Emma Davis.

Manuscript preparation for Chapter 1 (“Evaluating the suitability of nine shelterbelt species for dendrochronological purposes in the Canadian Prairies”) was completed by Emma Davis, with comments and editorial suggestions from Colin Laroque and Ken van Rees. The manuscript has been submitted to Agroforestry (Submission # AGFO1458), and is currently being reviewed at the time of thesis binding.

## **Chapter I**

### **Evaluating the suitability of nine shelterbelt species for dendrochronological purposes in the Canadian Prairies**

## **Abstract**

Shelterbelts have played an important role in prairie agriculture since the late 1800s; however, little is known about how these shelterbelts may be affected by climate change. The objective of this study was to determine if shelterbelt species express a common radial-growth signal within and between trees. The study focused on the annual tree-ring growth of the nine most common shelterbelt species of the Canadian Prairies: *Salix acutifolia* (acute willow), *Caragana aborescens* (caragana, or Siberian pea shrub), *Picea pungens* (Colorado spruce), *Fraxinus pensylvannica* (green ash), *Populus sp.* (hybrid poplar), *Acer negundo* (Manitoba maple), *Pinus sylvestrus* (Scots pine), *Ulmus pumila* (Siberian elm) and *Picea glauca* (white spruce). Tree core samples were collected near Saskatoon, Saskatchewan using traditional dendrochronological methods. The standardized growth of each species was compared with historical homogenized climate data in order to determine the key monthly climate variables impacting each species. Prior to this analysis, little was known about the suitability of six of these nine species for dendrochronological purposes. It was found that all species crossdate at a significant level, and that the three most dominant climate factors are able to account for up to 37% of the annual variation in tree-ring growth. The findings of this study suggest that all nine species are suitable, to varying degrees, for future dendrochronological research in the Canadian Prairies as well as having implications for shelterbelt systems elsewhere in the world. The top four species based on the four ranking criteria (interseries correlation, mean sensitivity, climate explanatory power, and commonality) were white spruce, acute willow, caragana, and Manitoba maple.

## **Key Words**

Shelterbelts, agroforestry, carbon sequestration, dendroclimatology

## **Introduction**

Shelterbelts have played an important role in the Canadian prairie landscape since the beginning of the 20<sup>th</sup> century (Kulshreshtha et al. 2010). In 1903, the Prairie Farm Rehabilitation Administration, located in Indian Head, Saskatchewan and currently known as the Agri-Environment Services Branch (AESB) Agroforestry Development Centre, began sending complimentary trees to farmers for planting on their properties when requested. Shelterbelts are commonly trees and shrubs planted in long rows around a farmstead or agricultural fields. They provide protection from wind (Wang and Takle 1995; Torita and Satou 2007) and aid to minimize the deleterious impacts of soil erosion and snow loss (Brandle et al. 2004; Agriculture and Agri-Food Canada 2009). Shelterbelts also play a significant role in mitigating carbon dioxide emissions: throughout the history of the Canadian shelterbelt program, approximately 218 megatons of CO<sub>2</sub> have been sequestered from the atmosphere (Montagnini and Nair 2004; Dixon et al. 1993). This speaks to the potential of shelterbelts to act as carbon credits for farmers as a method of offsetting the greenhouse gas emissions associated with land use change and agricultural pursuits. Other benefits of shelterbelts include their role in reducing the odor of farm animals (Lin et al. 2006; Tyndall and Colletti 2007, Tyndall and Grala 2008), decreasing building heating costs by up to 18 % (Liu and Harris 2007), and providing habitat for local wildlife.

Although it is difficult to identify the exact origins of the concept of planting trees to protect land and agricultural endeavors, it is believed that shelterbelts have been planted for well over 500 years (Droze 1977). The first known formal shelterbelts were planted in Scotland where in 1457 the Scottish Parliament suggested they be planted as a means of protecting agricultural productivity (Brandle et al. 2004; Droze 1977). In Russia, shelterbelt planting and agroforestry practices began in the early 18<sup>th</sup> century. It is evident from their lengthy history that shelterbelt planting is a time-tried solution that ameliorates certain aspects of environmental degradation that can result from agricultural practices. With close to six million seedlings being distributed each year in Canada from the AESB (Kulshreshtha and Kort 2005), the significant amount of shelterbelt trees planted in the Canadian prairies continues to grow.

The same growth can be seen in the collective economic value of shelterbelt systems in Canada. In a report by Kulshreshtha and Kort (2005), the services provided by the shelterbelt

trees planted in the Canadian Prairie Provinces between 1981-2001 provide environmental and social services valued at approximately \$132 million. With similar shelterbelt systems planted across the globe, the economic and environmental value of these trees and shrubs is truly immense.

Shelterbelt trees are inherently related to human activity, both because of the services that they provide to landowners and because they are planted according to the specifications and designs provided for each species. Particularly in the seedling stage of tree development, shelterbelt trees are greatly assisted in their establishment by landowners who might provide additional watering, weeding, and who may also apply fertilizer. This differs significantly from a natural forest system where seedlings are left on their own to become established in a safe site, and then once established, fend for their survival under a suite of natural ecological processes (Rooney and Waller 1998).

With enough trees planted in the Canadian prairies to circle the globe roughly 27 times (Agriculture and Agri-Food Canada 2009), it becomes apparent that these trees must, and will continue to have, an increasingly significant impact on the overall forested ecology of the Prairies as well as contributing to the biomass accumulation in the environment. By investigating the way in which individual tree species have grown in the past, it will be possible to make more informed decisions about which shelterbelt species to plant today in order to maximize their carbon storage capacity in the future as regional climates continue to alter.

At present there are 25 tree and shrub species available for ordering through the AESB, of which nine of the most commonly planted are the selected species for this study. The species sampled and analyzed include *Picea glauca* (white spruce), *Picea pungens* (Colorado spruce), *Pinus sylvestrus* (Scots pine), *Populus sp.* (hybrid poplar), *Fraxinus pensylvannica* (green ash), *Salix acutifolia* (acute willow), *Caragana aborescens* (caragana, or Siberian pea shrub), *Acer negundo* (Manitoba maple), and *Ulmus pumila* (Siberian elm). Having a wide range of species types, we set out to determine if and which of the most common hardwoods and conifers share a common growth signal within and between trees. Caragana, a drought tolerant shrub that is very commonly planted in Prairie shelterbelts systems, was also selected for analysis due to its importance as a prolific species. Of the nine chosen species, only three have been previously used for dendrochronological pursuits: The International Tree Ring Database of species used in

tree-ring research describes white spruce, Colorado spruce, and Scots pine as being known to crossdate across a region (Grissino-Mayer 1993), while Siberian elm and green ash are classified as having no known crossdating information or as unable to crossdate, and the remaining four species are not included in the database (Grissino-Mayer 1993). The objectives of this research are to determine 1) if shelterbelt trees, which are heavily influenced by humans, share a common growth signal; and 2) whether they are suitable for further dendrochronological research by understanding the degree to which their variation in radial-growth can be explained by local climate factors.

Trees and their annual-growth rings have long since been used as paleo-climate proxies, allowing researchers to create a chronological record describing past climate conditions (Fritts 1976; Schweingruber 1988; Schweingruber 1996; Speers 2010). To date, no such known analysis has been completed on what shelterbelt trees are able to reveal about the past climate of the Prairies, or if under their human influenced environment, they express a common growth signal between trees in an individual shelterbelt, and also from shelterbelt to shelterbelt.

## **Study Sites**

Sampling for this study took place in south-central Saskatchewan, near the city of Saskatoon, where long-term (1895 to present) homogenized climate data is available for climate analyses (Environment Canada 2010; Figure 1.1). Site selection was based on accessibility, although certain selection criteria had to be met in order for sampling to occur. The species of interest had to be present in greater numbers than what was required for our analysis, allowing for random sampling within the site. Additionally, consultation with the landowner provided preliminary information (i.e. shelterbelt age) that helped us determine whether sampling would proceed. The eight sample sites were located between 500 and 550 m above sea level (Table 1.1). Seven were clustered between the town of Asquith, and Saskatoon, and the eighth was located at Dorval, Saskatchewan, approximately 110 km north of Saskatoon (Table 1.1).

The study sites and the surrounding areas are classified as tall grass prairie with Chernozemic soils, and parent material of fluvial and glaciofluvial origin (Dale and Lewry, 2007). Located inland and relatively isolated from the moderating influences of the ocean, the climate of the Saskatoon region is highly variable and is considered to have a warm summer with

a continental climate (Dfb) (Environment Canada 2010). The mean monthly temperature for Saskatoon varies between  $-17.5^{\circ}\text{C}$  in January and  $18.5^{\circ}\text{C}$  in July (Environment Canada 2010, Figure 1.2). For our purposes, we considered the growing season of the shelterbelt species to span from April to September, as outside of this window, temperatures drop too low to reasonably expect any substantial above- or below-ground growth. Mean monthly precipitation varies throughout the year, with the summer months experiencing significantly more precipitation than in the winter. Average precipitation is highest in June (70 mm) and lowest in February (20 mm) (Environment Canada 2010, Figure 1.2).

## **Methods**

At each site, the appropriate tree or shrub species were identified and 20 individuals were randomly selected for sampling. Because of the inherent nature of shelterbelts being planted after 1903 and in far greater numbers more recently, the landowner was questioned when possible, as to the approximate age of the trees before sampling began. A minimum tree age of 30 years and preferably older than 50 years was necessary to complete statistically significant analyses (Grissino-Mayer 2001, Biondi and Waikul 2004). For all species excepting caragana, two core samples were taken from each tree at right angles from one another. The samples were collected at breast height using a 5.1 mm increment borer and stored in straws for transportation. Occasionally more than one species was sampled at each site.

Caragana was sampled differently than the tree species because it often has as many as 25 stems or branches growing outwards from one central root mass, and because the girth of individual stems is generally too small to sample using traditional methods. Instead of using increment borers, a healthy branch from the shrub was identified and removed using a reciprocating saw. From each branch that was sampled, a section approximately 15 cm in length was collected near the base of the stem for analysis. Individual shrubs were sampled randomly, about every three metres down a row of caragana, in order to minimize any impact on the function of the overall shelterbelt. Twenty caragana stems were sampled at each site.

In the lab, the tree core samples were prepared for analysis by first gluing the samples into slotted mounting boards, and then by sanding them with progressively finer sand paper (80 to 600 grit). Because the best possible surface was sought, each sample was then further buffed

to eliminate any fine dust particles that were trapped within the wood pores. Caragana samples were prepared by cutting each 15 cm sample in half with a band saw to create two discs. One disc was saved and the other was sanded and buffed in a similar manner to the tree core samples above.

The samples were initially visually crossdated (pattern matched) for common marker years of suppressed or increased radial growth (Stokes and Smiley 1968). The annual-ring widths of the cores and discs were then measured to 0.01 mm precision on a Velmex measuring stage and viewed through a 63X microscope. Measurements were computerized and recorded using the program Measure J2X (VoorTech 2011) and statistical crossdating was then conducted utilizing the computer program COFECHA (Holmes 1983). COFECHA functions by establishing a master chronology from the raw ring-width measurements, and then by comparing each individual core to the overall master chronology. A degree of correlation with the master chronology is provided for each individual core in addition to each segment within the core. This aids to identify missing or false rings, or to determine if a section was incorrectly measured. The data were analyzed in 30-year segments with a 15-year lag due to the limited age of most samples. While crossdating, care was taken to maximize sample depth, and so on only a few occasions did a sample need to be eliminated from the analysis because it was responding to some external factor other than what was influencing the common-radial growth within the group.

COFECHA also produces a statistical output that provides insight into the growth characteristics of each series of tree-ring measurements. The autocorrelation value produced by the analysis is the degree to which the previous-year's growth influences the current-year's growth. A high autocorrelation value would suggest that if a tree experiences a year of favorable growing conditions, which is reflected in a wide ring, the tree rings would also be larger in the following year in part because of the success of the previous-growing season. The mean sensitivity of a species is a statistical descriptor of how sensitive the growth of a particular species is to its surrounding environment (Fritts 1976; Grissino-Mayer 2001). A high degree of sensitivity indicates that the radial-tree growth is being more heavily influenced by a single overriding environmental parameter. This can be determined visually by the alternation of wide and narrow rings on a tree core or disc, while a core whose rings appear to be all of a similar

width is less sensitive (Stokes and Smiley 1968). The last key statistic used in this study is the interseries correlation value. This is a measure of the strength of the common growth signal that is being expressed within and between trees at a given site. For the purposes of this study, an interseries correlation value of 0.4228 was required to exceed the 99% confidence interval and to be considered significant.

Once a final master chronology was established for each of the nine species, the computer program ARSTAN (Cook 1985) was used to standardize the measurements by treating the data with a single detrending. This is a statistical method of eliminating the pattern of increased growth that is typically expressed in the early years of a trees life, as well as standardizing the measurements so that individual trees and different species of trees can be directly compared (Cook 1985).

The standardized-growth measurements were compared using a Pearson's Product Moment correlation matrix to identify the existence of any interspecies relationships. This analysis was deemed useful, as it would allow us to determine if similar species are responding to external factors in the same way. If this were the case, it may not be necessary to sample many different shelterbelt species in the future in order to acquire a complete picture of all species' responses to climate in a given area, as perhaps sampling only one species would suffice.

The standardized measurements of each series, along with historical homogenized climate data from Saskatoon, were run against each other through the program DendroClim2002 to determine the main climate factors influencing annual-radial growth (Biondi and Waikul 2004). The months of April of the previous-growth year, to September of the current-growth year, for both monthly temperature and precipitation variables, were selected for the analysis (a total of 36 predictors). This window was selected as it is considered to include the months with the most likelihood to influence the radial-growth of the nine shelterbelt species. DendroClim conducts both correlation and response function analyses, and provides an output that indicates which climatic variables are significantly related to growth (Biondi and Waikul 2004). The degree of significance of the correlation and response function tests are provided and are useful in demonstrating which climate factors are likely to be the strongest predictors of radial growth in terms of months in the current, and/or previous year, as well as in terms of a temperature and/or precipitation variable (Biondi and Waikul 2004).

From each of the nine DendroClim2002 outputs, the three climate factors that explained the highest degree of variation in radial growth were identified and selected for use in a multiple regression analysis. The resulting  $R^2$  value describes the degree to which these leading monthly climate factors are able to account for the annual variation in the ring width of each species. Trees with more variability explained by the three climate variables will be considered more valuable for any further dendrochronological studies. Only the top three variables per species were selected to eliminate any over-fitting.

Because of the limited age of the collected samples, the climate analysis for caragana had to be completed slightly different. For each parameter that is to be analyzed with DendroClim 2002, the chronology has to be 1.5 times longer than the number of climate predictors because of the lagged variables and the loss of a year by the degrees of freedom. The length of the caragana chronology was just below this threshold. Instead of creating dummy variables to extend the length of our chronology to be able to run the lagged component of the analysis (which would perhaps create errors of bias in the output), we chose to complete the analysis for only the current year's climate variables, excluding those of the previous years. We knew that this would produce slightly different results than if the previous and current years were analyzed simultaneously, but it was decided that it would be more accurate than fabricating dummy-year values to extend the short chronology.

Finally, each of the nine species was ranked in relative usefulness compared to the other species based on four characteristics: A) mean sensitivity values, B) interseries correlation values, C) variation explained by climate, and D) perceived commonality (an assigned variable based on the overall number of each tree species planted, reflecting the total numbers of trees per species sent out by AESB in 1960 or before). This was done in an effort to quantify the suitability of each of the nine species for further dendrochronological pursuits, and provides insight into where to focus future efforts into shelterbelt research.

## **Results**

Of the total 320 cores and 20 cookies from 180 individual trees and shrubs that were collected, 284 cores and 17 cookies were included in the final analysis, which account for an inclusion of 89% of the samples (Table 1.2). All of the species' chronologies were over 50 years

in length (ranging between 56-98 years), except the chronology of the shrub caragana, which was 34 years in length. This may be attributable to the short lifespan of individual caragana stems. A minimum interseries correlation value ( $r$ ) of 0.4228 was required to reach the 99% confidence level, based on a 30-year window that overlapped every 15 years. All nine crossdated species chronologies surpassed this confidence level and were found to correlate well within and between trees, with  $r$ -values ranging between 0.53 and 0.73 (Table 1.2). Autocorrelation values for the nine species ranged between 0.43 and 0.72. This level of autocorrelation values is deemed to be relatively high, based on accepted levels of the statistic for tree-ring chronologies (Grissino-Mayer 2001). The mean-sensitivity values for the nine species were consistent within a window of 0.26 and 0.46. This means that all trees in this study exhibit intermediate to high mean sensitivity based on previously established thresholds (Low: 0.10-0.19, Intermediate: 0.20-0.29, High:  $> 0.30$  respectively, Grissino-Mayer 2001).

The variation in relative age and mean sensitivity of each chronology become particularly apparent when compared graphically (Figure 1.4). Mean sensitivity is visually expressed by deviations above or below the mean-ring growth for a particular year. Caragana, for example, was found to have a low mean sensitivity and exhibits complacency in its variation when plotted over time. When compared to a more sensitive species (e.g., acute willow), the low deviation from the mean ring-growth from year-to-year for caragana stands out.

The results of the climate analysis outputs from DendroClim 2002 are depicted in Figure 1.4. The outputs of the individual analyses were graphed and display the variation in the influence of the climate factors on a monthly basis. The completion of this analysis illustrates that each species is responding to climate parameters in a different way. Conducting a multiple regression analysis that compared annual-radial growth to the top three climate variables (in terms of significant correlation as determined by the DendroClim analyses) provided an indication of the strength of the relationship between climate and annual-radial growth. The  $R^2$  value resulting from each analysis expresses the percentage of the variation in growth that is accounted for by the top three chosen climate variables (Table 1.2).

When the standardized ring-width measurements were compared between species using a Pearson's Product Moment correlation matrix, the strength of interspecies correlations ranged

from a low of 0.101 between caragana and hybrid poplar ( $p=0.571$ ), to a high of 0.702 between Scots pine and white spruce ( $p = 0.000$ ) (Table 1.3).

Determining which species are the most useful for dendrochronological studies is an important way of informing future investigations in shelterbelts. To do this, several key statistics resulting from the aforementioned analyses were noted for each species, which resulted in the ability to create a relative usefulness rank between all nine species (Table 1.4). Each species was ranked by the strength of its interseries correlation, mean sensitivity, the climatic influence, and commonality. Next, each species' scores from the four variables ranked were totaled (Table 1.4). For example, the species with the highest total score was white spruce (rank = 1, rank score = 32), based on it being ranked highest in terms of interseries correlation and mean sensitivity, and moderately well in terms of climate explanatory power (percentage of variation explained by three strongest climate variables). With a total score of 26 (out of a possible 36), it is considered the most useful species (tied with Acute willow).

## **Discussion**

While all plants have an essential need for light, water, nutrients and carbon dioxide, the way that these environmental inputs are expressed in their growth varies between species and through time. In our study, environmental sensitivity, interseries correlation, significant climate variables and other summary statistics varied between each species, and these parameters have a role in determining which species are more or less useful for dendrochronological studies. It is worth noting that even the species that rank among the lowest of those studied still crossdated successfully, and therefore can provide valuable insight into past environmental conditions where they grow, although some more than others. The species are discussed individually below in their ranked order to explain their variation and degree of usefulness.

### ***Picea glauca* (white spruce) – Usefulness Rank: 1**

Of the nine species studied, the 66-year master chronology of white spruce demonstrated the strongest interseries correlation ( $r=0.73$ ,  $n=40$  cores). This suggests that in our study, white spruce was demonstrating the strongest common growth signal within and between trees. White spruce also had the highest mean sensitivity value (0.46), indicating that the surrounding environment has a strong impact on the variation in yearly growth for this species. The strongest

interseries correlation and mean sensitivity values, in addition to a high ranking in the explained variance by climate variable (fourth highest), make white spruce a very suitable species for climate modeling. In our study, it was ranked as the most useful for future dendrochronological purposes (tied with acute willow), and is a preferred species for its ease in the crossdating process (Table 1.4).

Statistical analysis between historical climate data and annual growth provided insight into the driving climate factors accounting for year-to-year variability in ring-width growth. White spruce tree-ring growth appeared to be heavily influenced by the previous year's August temperature (negative correlation), the current year's July temperature (negative), previous September precipitation (positive), and current June precipitation (positive). It was found that the three most significant climate factors accounted for 28% of the variation in annual growth.

The standardized growth of white spruce compared well to that of other species, in particular it closely resembled hybrid poplar, acute willow, Colorado spruce, Siberian elm, Manitoba maple, and Scots pine, as each of these species were found to correlate with it above a significant level ( $p < 0.01$ ). The annual growth of white spruce and Scots pine was particularly similar, with a correlation value over 0.70.

### ***Salix acutifolia* (acute willow) – Usefulness Rank: 1**

Acute willow had the second highest interseries correlation value of the nine species studied ( $r=0.72$ ), and the length of the master chronology was 56 years ( $n=34$  cores). The three climate factors that had the biggest impact on the annual ring width variation of acute willow were previous September precipitation (positive correlation), June precipitation (positive), and June temperature (negative). These three factors have the combined explanatory power of 35% of the variance in radial growth.

Acute willow appears to be suitable for dendrochronological uses based on this data, a fact that was further supported by its rank as tied for the most useful species (Table 1.4). The combined impact of the high interseries correlation value, and the high explanatory power of the main climate factors, suggests that acute willow has the potential to be a useful species for various sub-disciplines of dendrochronology. Currently not listed in Grissino-Mayer (2007)

database, acute willow should be considered for addition, as it was easily able to be crossdated within and between trees.

### ***Caragana aborescens* (caragana) – Usefulness Rank: 3**

Prior to this study, the annual growth characteristics of caragana were largely a mystery. It was unknown whether the species produced annual-growth rings, or if its life span was long enough to produce a viable chronology. Our analysis produced a master chronology that was 34 years in length (n=17 discs), with an interseries correlation value of 0.61. The mean sensitivity of caragana was 0.26, the lowest of the nine species sampled. This indicates that while the shrubs in one area are responding to a similar annual growth signal, the year-to-year variability in the response as expressed by the width of annual rings is very low. In essence, caragana seems to grow well under a series of varying climatological inputs, and is not overly sensitive to one limiting factor.

The annual growth of caragana did not correlate well with the other species. A significant relationship was identified between Colorado spruce, Scots pine, and Siberian elm ( $p < 0.05$ ) (Table 1.3). This relationship suggested that the environmental factors that caragana was responding to differs from the other species studied. The three main climate factors (May temperature (negative correlation), June temperature (negative), and June precipitation (positive), for caragana, accounted for 37% of the annual variability in its ring-width growth, the most of any of the nine species studied.

The strength of the interseries correlation value, the high accountability of the three dominant climate factors to explain much of the year-to-year variability in growth, in addition to its rank as the third most useful species suggests that caragana is a suitable species for further dendrochronology. Additionally, caragana was the most prolific species of the nine sampled, therefore contributing significantly to the overall shelterbelt biomass of the prairies. Caution should be taken while sampling, however, as despite its abundant nature, the stems of this shrub do not appear to live long past the 30 years necessary for a minimum statistically significant analysis. Increasing the amount of samples collected in the field may improve the likelihood of collecting older samples, as many of the samples had rot in their centers.

#### ***Acer negundo* (Manitoba maple) – Usefulness Rank: 4**

The interseries correlation value for Manitoba maple was 0.59 (n=33 cores) with a master chronology 57 years in length. The annual rings for this species were difficult to discern under a microscope, but became more visible with additional sanding and buffing (up to 1000 grit). Current September temperature (negative correlation) appeared to be the dominant climate factor, in addition to previous October temperature (negative) and previous December temperature (negative). These three variables combined to account for 21% of the annual variability of ring-width growth. Manitoba maple can be considered to effectively crossdate within and between trees at a given location.

The annual growth of Manitoba maple corresponded well to that of several of the other species studied: acute willow, hybrid poplar, Colorado spruce, Siberian elm, white spruce, and Scots pine in particular ( $p < 0.01$ ) (Table 1.3). Due to its high mean sensitivity (rank score = 8) and intermediate rankings of interseries correlation (rank score = 4) and explained climate (rank score = 3), Manitoba maple is considered to be the fourth most useful species in our study (Table 1.4). For these reasons, in addition to Manitoba maple's relative abundance in the prairies (rank score = 8), this species should be added to the list of useful species for dendrochronology.

#### ***Fraxinus pensylvannica* (green ash) – Usefulness Rank: 5**

Although difficult to core in the field, green ash crossdated with ease, providing the second longest chronology (96 years), and a relatively high interseries correlation value of 0.63 from 37 cores (Table 1.2). The main climate variable controlling the growth of green ash is previous June precipitation (positive correlation), current June precipitation (positive), and June temperature (negative). These main three climate factors contributed to 15% of the annual variability in radial growth, and suggest that green ash is responding predominantly to the climatic conditions of the month of June.

When compared to the other eight species sampled, the green ash signal correlated with acute willow, Siberian elm, hybrid poplar, Scots pine, and white spruce at the 99% confidence interval (Table 1.3).

This species is listed as ‘not being able to crossdate, or having no information available’ on Grissino-Mayer’s (2007) tree ring database. While the high degree of interseries correlation suggests that green ash is likely suitable for dendrochronological purposes, the low explanatory power (rank score = 1) of the top three climate factors suggests that perhaps green ash is not as appropriate for studies pertaining to climate, despite its intermediate ranking of commonality (Table 1.4).

***Populus sp. (hybrid poplar) – Usefulness Rank: 6***

The master chronology for hybrid poplar proved to be the longest of all nine species (98 years, n=37 cores). Hybrid poplar expressed an annual growth pattern that correlated at a significant level with acute willow, white spruce, Manitoba maple, and Scots pine (Table 1.3). The set of samples expressed a high interseries correlation value (0.70), but despite this, hybrid poplar was ranked on the lesser side of usefulness for dendrochronology because of its relatively low mean sensitivity ranking (rank score = 3), its low climate explanatory power ranking (rank score = 2), and its intermediate abundance in the field (rank score = 6).

The main climate factors controlling the majority of the year-to-year ring-width variability were previous August temperature (negative correlation), current July temperature (negative), and previous September precipitation (positive).

Prior to this study, little was known about the ability of hybrid poplar to crossdate, or how it responds to climate variables. Based on the details outlined above, hybrid poplar can be considered to successfully crossdate within and between trees, but if time or resources were limited, our assessment would recommend that other species would be more useful for dendrochronological pursuits.

***Picea pungens (Colorado spruce) – Usefulness Rank: 7***

The master chronology for Colorado spruce was 58 years in length (n=38 cores). The interseries correlation for this species was among the lowest ( $r=0.58$ ), but was still well above the 0.4228 cut off value required for a significant correlation above the 99% level (Table 1.2). The mean sensitivity was low for Colorado spruce (0.27) when compared to white spruce (0.46), indicating that while white spruce and Colorado spruce appear morphologically similar in the

field, they are responding differently to environmental conditions. Notably, Colorado spruce was one of only three of our species that were included in Grissino-Mayer (2007) database, and had it the second lowest interseries correlation value.

Colorado spruce ranks seventh among the other species in terms of usefulness for dendrochronological purposes (Table 1.4). This was due to a low mean sensitivity ranking and low interseries correlation value. Colorado spruce, however, had one of the highest climate explanatory powers (rank score = 7) and an intermediate level of commonality (rank score = 5).

When analyzed with historical climate data in DendroClim2002, Colorado spruce appeared to be responding largely to three main climate factors. Previous July temperature (negative correlation), current April precipitation (positive) and current July precipitation (positive) accounted for most of the explained year-to-year variability in ring-width growth. These three monthly climate factors were found to account for 34% of the annual variation in radial-ring growth.

The annual ring-width growth of Colorado spruce produced significant relationships with acute willow, green ash, Manitoba maple, Scots pine, Siberian elm, and white spruce at the 99% confidence interval, and caragana 95% confidence interval.

### ***Ulmus pumila* (Siberian elm) – Usefulness Rank: 8**

Siberian elm proved challenging to crossdate, but it resulted in a master chronology of 55 years with an interseries correlation value of 0.58 (n=32 cores). The monthly climate variables accounting for the majority of the variability in growth were previous September precipitation (positive correlation), current June temperature (negative), and current June precipitation (positive). This indicated that the species' annual growth is heavily linked to the environmental conditions in the month of June. These three variables accounted for 26% of the annual variability. The annual growth of Siberian elm correlated significantly with acute willow, Colorado spruce, Manitoba maple, white spruce, and Scots pine at the 99% confidence interval (Table 1.3).

Siberian elm ranked low in relative interseries correlation (rank score = 3), commonality (rank score = 3), only moderately well in mean sensitivity (rank score = 4), and climate

explanatory power (rank score = 5) relative to the other species. For this reason, it is among the group of low ranking species in terms of usefulness (Table 1.4). Although not among the best shelterbelt species for dendrochronological analyses, it is notable that it did crossdate successfully within and between trees.

### ***Pinus sylvestrus* (Scots pine) – Usefulness Rank: 9**

Scots pine samples produced a 57-year chronology (n=33 cores) with an interseries correlation value of 0.53 (Table 1.2). This is the lowest interseries correlation value of all of the species studied, but is still considered to be significant. A variety of climate factors appear to be driving the annual variation in ring-width growth for this species. The response function analysis revealed relationships to previous November temperature (positive relationship), current July temperature (negative), as well as a positive relationship to previous September precipitation, and current January and June precipitation variables (January precipitation may be linked to effects of snow pack). These results indicated that the annual growth of Scots pine is influenced to a greater extent by precipitation than by temperature.

The annual growth of Scots pine correlated significantly with all species at the 99% confidence interval, except caragana (95% confidence interval) (Table 1.3).

Scots pine ranked among the least useful species because of its relatively low interseries correlation value (ranked score = 1) and low abundance (rank score = 1). It did, however, have the third highest mean sensitivity value, (rank score = 7), suggesting that while the influential climate factors vary widely, this species is sensitive to its climatic environment in the same manner across a site.

Based on the numerous significant interspecies correlations between Scots pine and other species, in addition to its low overall usefulness ranking, it may be suitable to forego sampling Scots pine in shelterbelts and to focus efforts on species with similar growth patterns that have been shown to be more useful for dendrochronology (such as white spruce and acute willow, for example).

## **Conclusion**

This study set out to determine if shelterbelt tree species in the Canadian Prairies express a common annual-growth signal within and between trees in an effort to demonstrate their potential use in dendrochronological analyses. There are millions of shelterbelt trees and shrubs planted in the Canadian Prairies, and millions more planted around the world, but as our results indicate, they are not all created equal in terms of their usefulness for dendrochronology.

Based on the criteria of interseries correlation, mean sensitivity, the degree of variation explained by the three most explanatory climate factors and commonality, we have ranked the nine most common species in order of usefulness (Table 1.4). It has been determined that future efforts in sampling Canadian Prairie shelterbelts tree species should be focused on white spruce, acute willow, caragana, and Manitoba maple, as they were found to be the most useful for dendrochronological purposes. Although caragana stems may not capture as long of a record in their rings, this shortcoming is balanced by its high climate explanatory power and its prolific nature across the Prairies.

The results of this study suggest that all nine species successfully express a common annual growth signal within and between trees, but that some are more useful than others. Given limited time or resources, it would therefore be beneficial to focus efforts on the four highest-ranking species for future studies of dendrochronology and dendroclimatology.

## **Acknowledgements**

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## Tables

**Table 1.1** Site characteristics of the nine species sampled.

<b>Species</b>	<b>Latitude (N)</b>	<b>Longitude (W)</b>	<b>MASL (m)</b>
Acute Willow	52°08'13.4"	107°14'32.6"	521
Caragana	52°04'57.2"	107°18'45.9"	545
C. Spruce	52° 54'55.0"	106°13'19.3"	501
Green Ash	52°00'46.0"	107°13'02.7"	536
Hybrid Poplar	52°06'37.4"	107°18'34.8"	539
M. Maple	52° 07'49.2"	107°08'42.2"	503
Scots Pine	52°07'28.7"	107°14'32.9"	533
Siberian Elm	52° 07'49.2"	107°08'42.2"	503
White Spruce	52°04'40.2"	107°18'50.5"	548

**Table 1.2** Individual chronology statistics summarizing the growth characteristics of each species that describe the length of the chronology, interseries correlation value, autocorrelation value, mean sensitivity, and the degree of influence the three most significant climate variables have on each species. (*Time* – timeframe of master chronology, *Cores* – tree cores used in final chronology, *Corr.* – Interseries correlation value, *Auto.* – Autocorrelation value, *Sens.* – Mean sensitivity value, *Length* – length of chronology, *Climate* – Influence of climate)

<b>Species (Common)</b>	<b>Time</b>	<b>Cores</b>	<b>Corr.</b>	<b>Auto.</b>	<b>Sens.</b>	<b>Length</b>	<b>Climate</b>
<i>Salix acutifolia</i> (Acute Willow)	1955- 2010	34	0.72	0.53	0.37	56	0.35
<i>Caragana</i> <i>Aborescens</i> (Caragana)	1977- 2010	17	0.61	0.43	0.26	34	0.37
<i>Picea pungens</i> (Colorado Spruce)	1953- 2010	38	0.58	0.62	0.27	58	0.34
<i>Fraxinus</i> <i>pensylvannica</i> (Green Ash)	1915- 2010	37	0.63	0.63	0.34	96	0.15
<i>Populus sp.</i> (Hybrid poplar)	1913- 2010	37	0.70	0.72	0.31	98	0.21
<i>Acer negundo</i> (Manitoba maple)	1954- 2010	33	0.59	0.52	0.45	57	0.22
<i>Pinus sylvestrus</i> (Scots pine)	1927- 2010	33	0.53	0.63	0.38	84	0.24

<i>Ulmus pumila</i> (Siberian elm)	1956- 2010	32	0.58	0.55	0.33	55	0.25
<i>Picea glauca</i> (White Spruce)	1945- 2010	40	0.73	0.53	0.46	66	0.28

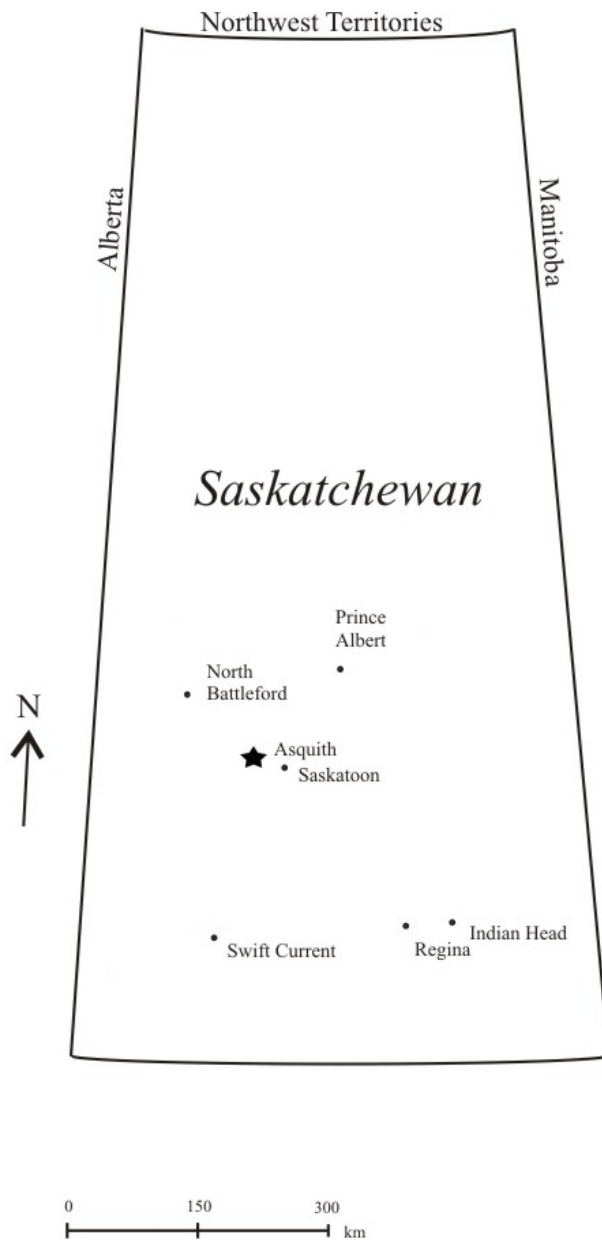
- 1 **Table 1.3** A Pearson's Product Moment Correlation matrix demonstrating the relationship between species master chronologies.
- 2 Interspecies correlations values are listed, with *p* values in brackets below. Dark grey blocks represent significant relationships above the 99% confidence interval, and light grey represents significant relationships above the 95% confidence interval.
- 3

Species	A. willow	Caragana	C. spruce	G. ash	H. poplar	M. maple	S. pine	S. elm	W. spruce
<b>Caragana</b>	0.319 (0.066)								
<b>C. spruce</b>	0.435 (0.001)	0.431 (0.011)							
<b>G. ash</b>	0.45 (0.000)	0.326 (0.060)	0.413 (0.001)						
<b>H. poplar</b>	0.568 (0.000)	0.101 (0.571)	0.250 (0.059)	0.343 (0.001)					
<b>M. maple</b>	0.422 (0.001)	0.227 (0.197)	0.471 (0.000)	0.356 (0.007)	0.436 (0.001)				
<b>S. pine</b>	0.590 (0.000)	0.342 (0.048)	0.406 (0.002)	0.342 (0.001)	0.448 (0.000)	0.537 (0.000)			
<b>S. elm</b>	0.348 (0.009)	0.339 (0.050)	0.426 (0.001)	0.267 (0.049)	0.278 (0.040)	0.349 (0.009)	0.521 (0.000)		
	0.638	0.291	0.456	0.363	0.548	0.489	0.701	0.54	

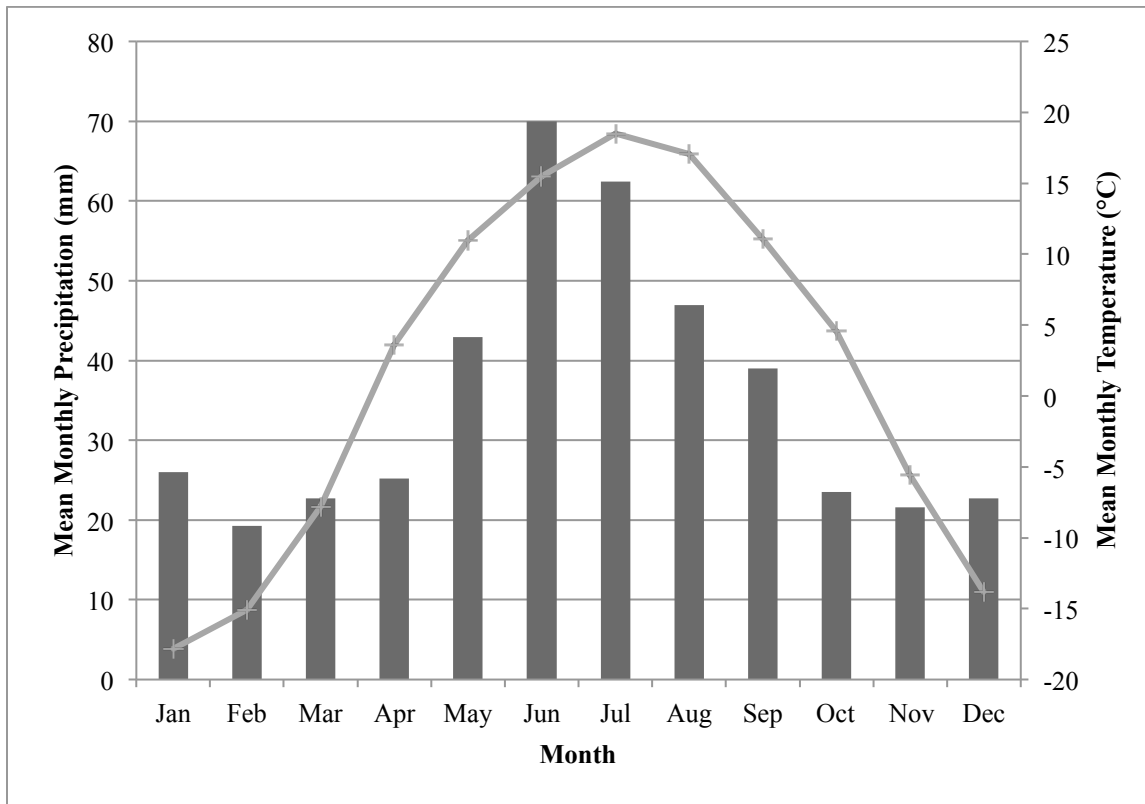
**Table 1.4** Usefulness ranks for each species, based on interseries correlation, mean sensitivity, explanatory power in terms of climate, and commonality. Each species was ranked on a basis with 9 as the highest and 1 as the lowest. The resulting totals were then converted to ranks. Species are listed in order of most to least useful for dendrochronological analysis.

<b>Species</b>	<b>Inter. Corr.</b>	<b>Sensitivity</b>	<b>Climate</b>	<b>Commonality</b>	<b>Total</b>	<b>Rank</b>
<b>White spruce</b>	9	9	6	2	26	1
<b>Acute willow</b>	8	6	8	4	26	2
<b>Caragana</b>	5	1	9	9	24	3
<b>Manitoba maple</b>	4	8	3	8	23	4
<b>Green ash</b>	6	5	1	7	19	5
<b>Hybrid poplar</b>	7	3	2	6	18	6
<b>Colorado spruce</b>	3	2	7	5	17	7
<b>Siberian elm</b>	3	4	5	3	15	8
<b>Scots pine</b>	1	7	4	1	13	9

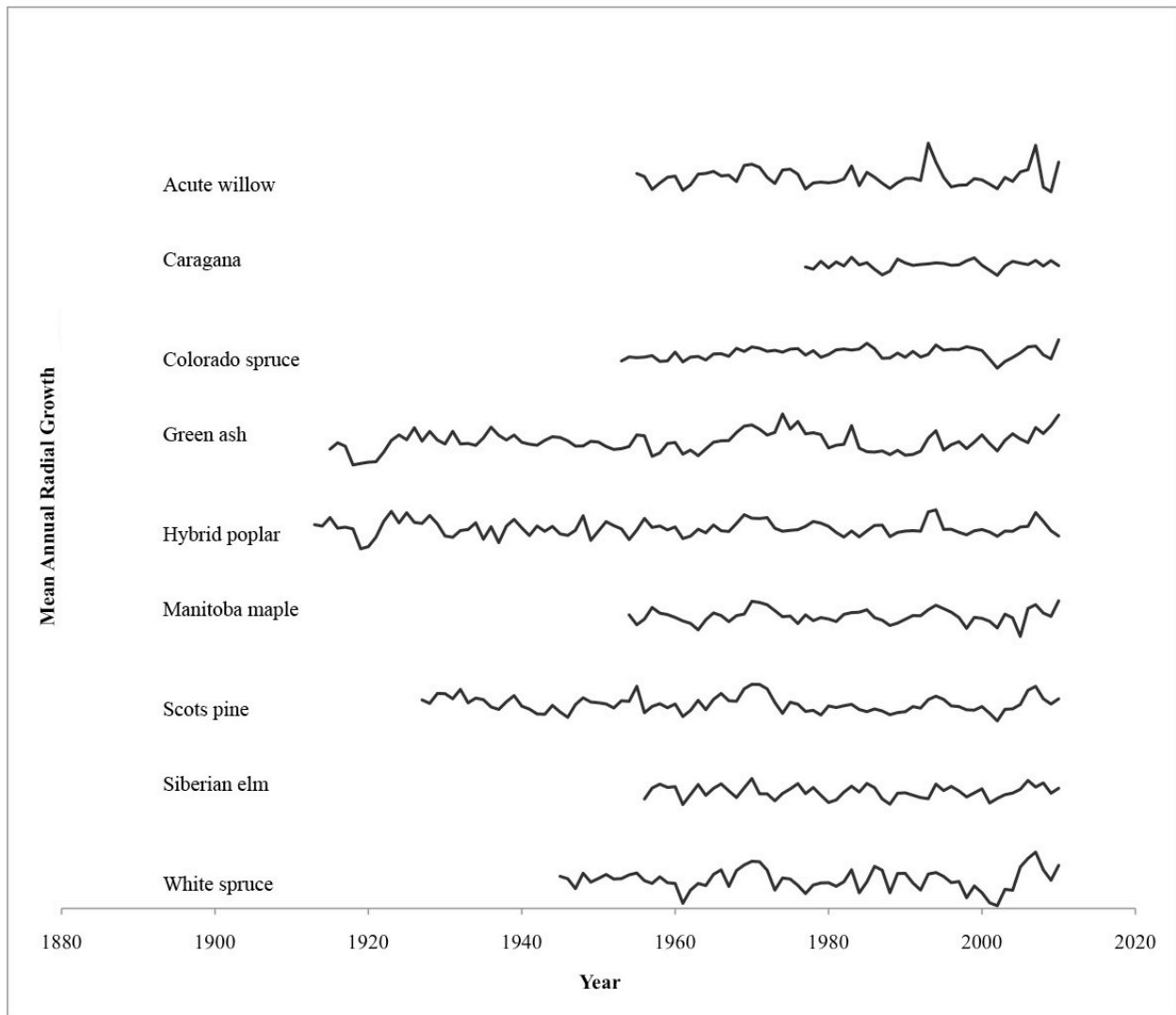
## Figures



**Figure 1.1** Map of the province of Saskatchewan. Most samples for this study were collected near Saskatoon, in the town of Asquith with Colorado spruce samples collected 110 km to the northeast towards Prince Albert.



**Figure 1.2** Mean monthly temperature and precipitation data for Saskatoon, SK (1900-2008) (Environment Canada 2010). The line represents the change in annual mean-monthly temperature, and the bars provide an indication of mean-monthly precipitation. The data presented here is derived from the climate data used for later analyses.



**Figure 1.3** Master chronologies of the nine species, demonstrating standardized ring-width growth over time.



**Figure 1.4** The nine Dendroclim2002 analyses for A) Acute willow; B) Caragana; C) Colorado spruce; D) Green ash; E) Hybrid poplar; F) Manitoba maple; G) Scots pine; H) Siberian elm; I) White spruce. The independent axis is the correlation index created by the output, indicating the degree of correlation between ring growth and the particular climate variable. The upper and lower boundary lines indicate the degree of correlation required between the monthly climate variable and the corresponding standardized ring-width growth to be considered significant at the 95% confidence interval. Any bar that crosses this linear threshold, therefore, is considered to be a significant factor in the individual species' growth. The circular marker implies the attainment of a significant response function variable for the corresponding monthly climate variable.

## **Chapter II**

### **Radial-growth Forecasting: the projected status of nine shelterbelt species in 2100**

## **Abstract**

Millions of shelterbelt trees and shrubs have been planted in the Canadian Prairies over the last 100 years. Shelterbelts have the potential to sequester a significant amount of CO<sub>2</sub> from the atmosphere, along with improving the biotic and abiotic conditions of the local environment. This study investigates historical relationships between annual radial-growth measurements and various environmental parameters, with the aim of forecasting future radial-growth trends under three different climate scenarios (CGCM3 T47). A stepwise-multilinear regression was completed for nine of the most commonly planted shelterbelt species with the intention of qualitatively classifying the likely future growth tendencies of each species. The results of our analysis demonstrate that most species will either experience moderately suppressed or stable growth into the future, indicating that certain species should be preferentially planted because of their favorable or unaffected response to projected changes in climate.

## **Keywords**

Shelterbelts, climate change, radial-growth forecasting, agroforestry, Canadian Prairies

## **Introduction**

Shelterbelts have been distributed free of charge to landowners in the Canadian Prairies since 1903. Initially used to combat the effects of soil erosion that followed years of drought and land conversion, many of the value-added properties of shelterbelts have become apparent through time. Shelterbelts are known to provide a habitat for wildlife, reduce wind speeds around properties, and improve home heating efficiency (Shoeneberger 2008). As we enter into an era with growing concerns surrounding climate change, shelterbelts are now being recognized as having a new and vital role to play in Prairie ecosystems - sequestering carbon from the atmosphere.

Shelterbelt systems possess a particular benefit in that they sequester a sizable amount of carbon dioxide from the atmosphere while leaving the majority of land available for other (agricultural) uses (Shoeneberger 2008). This makes them easy to incorporate into the landscape of existing properties. Past studies have demonstrated that the carbon content of shelterbelt systems is readily quantifiable. Kort and Turnock (1999) measured the above ground carbon content of five commonly planted shelterbelt species, and found that it ranged from 32 t/km to 105 t/km. With thousands of kilometres of property line throughout the Prairies, the potential for shelterbelts and agroforestry is extensive.

The purpose of this research is to aid in quantifying the carbon sequestering capacity of the nine most commonly planted shelterbelt species in the Canadian prairies. This was completed by exploring the relationships between historical radial-growth measurements and environmental variables, and by forecasting future growth under three different climate scenarios. Radial-growth forecasting has been used in the past to model future tree growth (Laroque and Smith 2003; Phillips 2009; Selig 2009; Kennedy et al. 2010). Following these already established methods, models were created for each of the nine species encompassing a variety of environmental factors that have been shown to influence annual tree-ring growth (Davis et al. 2012). Currently, species selection is based largely on growth rate, aesthetics, or availability. By attempting to forecast how each of the species will respond to future climate scenarios, it is possible for land owners to make more informed choices when deciding which species to plant on their properties.

## **Study Sites**

All tree and shrub samples were collected near Saskatoon, Saskatchewan (52°N, 107°W) (Figure 1.1, Table 1.1). At each site, 40 cores were collected from the shelterbelt species, except for the shrub caragana (20 cookies were collected using a reciprocating saw). The eight study sites were located within 110 km of Saskatoon, where historical climate data is available, although most sites were less than 50 km from Saskatoon.

## **Methods**

### **Tree-Ring Data**

At each site, 20 individual trees or shrubs were selected for sampling. Whenever possible, the landowner was questioned as to the age of the shelterbelts, as older specimens allow for the establishment of a longer and more statistically robust growth chronology (Grissino-Mayer 2001, Biondi and Waikul 2004). A minimum shelterbelt age of 30 years was required for our purposes, although samples older than 50 years were preferred. For the tree species, two samples were collected at breast height using a 5.1 mm increment borer, resulting in a sample depth of 40 cores per species. The samples were stored in straws for transportation. For the shrub species caragana, samples were collected using a reciprocating saw. This was because each shrub possesses upwards of 25 stems per plant, with no single stem being large enough to sample with traditional methods. It was deemed that this minimally intrusive form of destructive sampling would not harm the overall function of the shelterbelt. Twenty caragana cookies were collected from our sample site.

Once they were transported back to the lab, the tree cores were prepared by gluing the samples into slotted mounting boards. The boards were left to air dry, and were then sanded to a progressively finer polish (up to 600 grit). The samples were then buffed to eliminate particulate matter that may have become trapped in the wood pores. Caragana cookies were prepared by cutting a 5 cm section from each sample collected in the field. Each section was then sanded and buffed similarly to the tree cores.

The prepared tree and shrub samples were initially visually pattern matched (crossdated) for years of increased or suppressed radial growth (Stokes and Smiley 1968). Ring-widths were then measured using a 63X microscope and a mounted Velmex measuring stage to 0.001 mm

precision. The computer software Measure J2X (VoorTech 2011) was used to digitally record the measurements, and the program COFECHA was used to aid in the crossdating process (Holmes 1983). COFECHA establishes a master chronology from the recorded raw ring-width measurements, and then compares the measurements of each individual core or cookie to the overall master chronology. This provides a degree of correlation between each sample and the master chronology, as well as an indication as to whether false or missing rings are present. The recorded data was analyzed in 30-year segments with a 15-year lag due to the limited age of some of the samples.

COFECHA produces a useful statistical output that provides certain indications about the radial-growth characteristics of each species. The autocorrelation value is the degree to which the previous year's growing season influences the current year's growth (a lag effect). The mean sensitivity is a descriptor of how responsive the particular species is to environmental conditions (Fritts 1976; Grissino-Mayer 2001). Species with a high mean sensitivity possess a visible alternation in wide and narrow growth rings in response to changing environmental factors from year to year (Stokes and Smiley 1968). The interseries correlation value is a statistic of importance as it indicates how well each species expresses a common annual-growth signal within and between trees. For this analysis, an interseries correlation value of 0.4228 was required to be considered significant at the 99% confidence interval.

Once the samples were crossdated, a master chronology was established using the computer software ARSTAN (Cook 1985). ARSTAN standardizes the annual radial-growth measurements to eliminate the trend of increased growth that is often expressed in the early years of a tree's life. This also creates a standardized growth index so that the growth patterns of different species may be compared directly (Cook 1985).

### **Historical Climate Data**

Climate data was obtained from Environment Canada's database of Adjusted Historical Canadian Climate Data (Environment Canada 2010) available for Saskatoon, Saskatchewan. Although the data covered a lengthy time span (1900-present), gaps existed in the continuity of the information. For the purposes of this analysis, a complete data set was required to model future growth, and so steps were taken to infer temperature and precipitation data in instances of

missing points. Whenever possible, missing climate values were estimated using the mean temperature or precipitation of the three years previous to and following the missing variable. When several consecutive years of missing data were present, the overall mean value of that variable was used. Because all sample sites were within 47 m of elevation, it was deemed unnecessary to correct climate data for elevational differences.

### **Establishing Climate Variables**

To forecast future growth, a variety of climate variables were created. These variables are what are used to model future growth by determining the influence each factor has historically had on radial growth. For the purposes of this analysis, basic climate variables were used. These included mean monthly temperature and precipitation of the current and previous year, and a winter precipitation variable. Temperature and precipitation were derived directly from established historical climate data, while winter precipitation was calculated from the mean precipitation values for November and December of the previous year, and January, February, and March of the current year. It was the hope that this variable would account at least in part for possible effects of winter snowpack depth. Tree-ring analyses conducted for the nine shelterbelt species have demonstrated that the previous year's climatic conditions influence radial growth, indicated by a high autocorrelation value (Table 1.2). It was, therefore, important to include the previous year's climate conditions as possible model variables.

### **Future Climate Data**

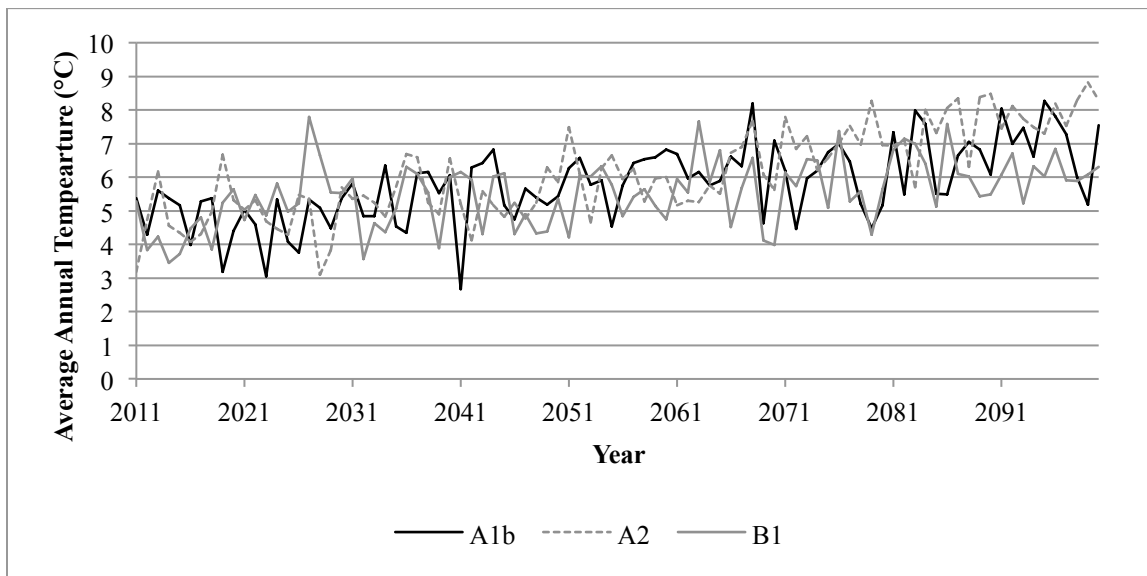
Future growth modeling was completed using three different climate scenarios established by the Inter-governmental Panel on Climate Change (IPCC 2007). The scenarios are based largely on different responses of humans to climate change. The SRES' (special report on emission scenarios) used for this analyses describe possible future conditions as follows:

*A1b* – The A1b scenario implies that the world will experience rapid economic growth and a global population peak in the mid twenty-first century. This scenario takes into account rapid introduction of technologies and greater economic equitability. The A1b scenario places a reliance on diverse energy sources, rather than on only one resource (IPCC 2007).

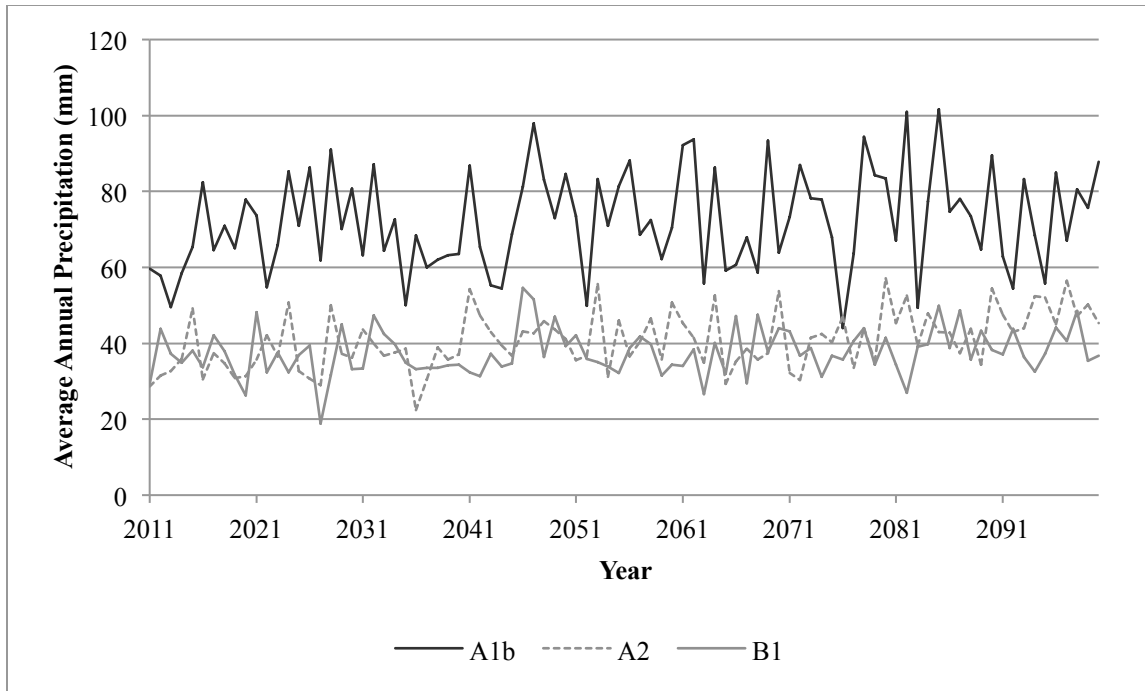
*A2* – The A2 scenario describes a heterogeneous world, with the maintenance of local identities. The population increases continuously, and economic development is pursued regionally. Technological growth is slow for SRES A2 (IPCC 2007).

*B1* – Under SRES B1, the global population peaks in the mid twenty-first century and declines thereafter. There is an emphasis on the creation of a ‘convergent world’, where solutions to economic, environmental, and social sustainability are sought on a global scale (IPCC 2007).

The future climate data was derived from CGCM3 T47 (Environment Canada 2010b). Data was obtained for the six grid cells covering the southern half of the province and an average of the values was taken. The future climate models indicate a trend in rising temperature between 2010 and 2100 (Figure 2.1) and a modest increase in precipitation (Figure 2.2). This suggests that the future climate of southern Saskatchewan will be both warmer and drier.



**Figure 2.1** Predicted mean-annual temperature based on SRES A1b, A2, B1 (2011-2100)



**Figure 2.2** Predicted mean-annual precipitation based on scenarios A1b, A2, B1 (2011-2100)

### Analysis

Future growth models were established for each species using the statistical software SPSS (IBM 2012). A stepwise-multilinear regression was completed using an F-probability value of 0.05-0.15 as per the methods of Phillips (2009), and Phillips and Laroque (2007). For the analysis, tree-ring growth was entered as the dependent variable and the climate data as the independent variables. A verification period encompassing the earliest 30% of the data was used, with calibration encompassing the remaining 70%. SPSS produces a variety of possible models, and so a consistent selection criterion was used to determine the model of best fit. Akaike's Information Theory correction criterion (AICc) was selected as an indicator of the most suitable model (the lower the AICc value, the more suitable the model) (Burnham 2002).

To determine the generalized future radial-growth trend of each species, qualitative criteria were established to reflect tendencies of suppressed, increased, or stable future growth. Species exhibiting between a +/- 10% departure from current standardized growth were considered stable. Those species with a +/- 11-20% change in average growth were classified as

experiencing moderate changes. Species experiencing extreme changes were classified as those demonstrating a >21% departure from the historical mean.

## **Results**

### **Tree Ring Analysis**

A total of 284 cores and 17 cookies were included in the final analysis, for an inclusion rate of 89% (Table 1.2). The master chronologies were between 34 and 98 years in length, for the most part, well above the minimum 30 years required for a statistically significant analysis. Caragana had the shortest chronology, likely due to the limited lifespan of individual stems.

The minimum required interseries correlation value of 0.4228 was surpassed for all species, demonstrating that they successfully crossdate within and between trees (Table 1.2). The autocorrelation values ranged between 0.43 and 0.72, suggesting that the environmental conditions of the previous growing season have a relatively important influence on the current year's ring-width growth (Grissino-Mayer 2001). The mean sensitivity values ranged between 0.26 and 0.46, an expression of intermediate to high environmental sensitivity in all shelterbelt species analyzed (Grissino-Mayer 2001).

### **Radial-growth Forecasting**

The nine shelterbelt species produced varied responses to future climate scenarios. The modeled calibration period was able to explain between 13.24 – 66.42% of the annual variation in tree-ring growth. The verification period explained between 1.80 – 39.38% of the variability (Table 2.1).

**Table 2.1** Results of the correlation between modeled growth and actual standardized growth measurements for nine shelterbelt species

<b>Species</b>	<b>Calibration Period (R)</b>	<b>Verification Period (R)</b>
Acute willow	0.648	0.391
Caragana	0.519	0.626
Colorado spruce	0.578	0.382
Green ash	0.364	0.134
Hybrid poplar	0.706	0.381
Manitoba maple	0.579	0.112
Scots pine	0.675	0.177
Siberian elm	-	-
White spruce	0.815	0.324

The following section will detail the individual results of the model analyses for each shelterbelt species.

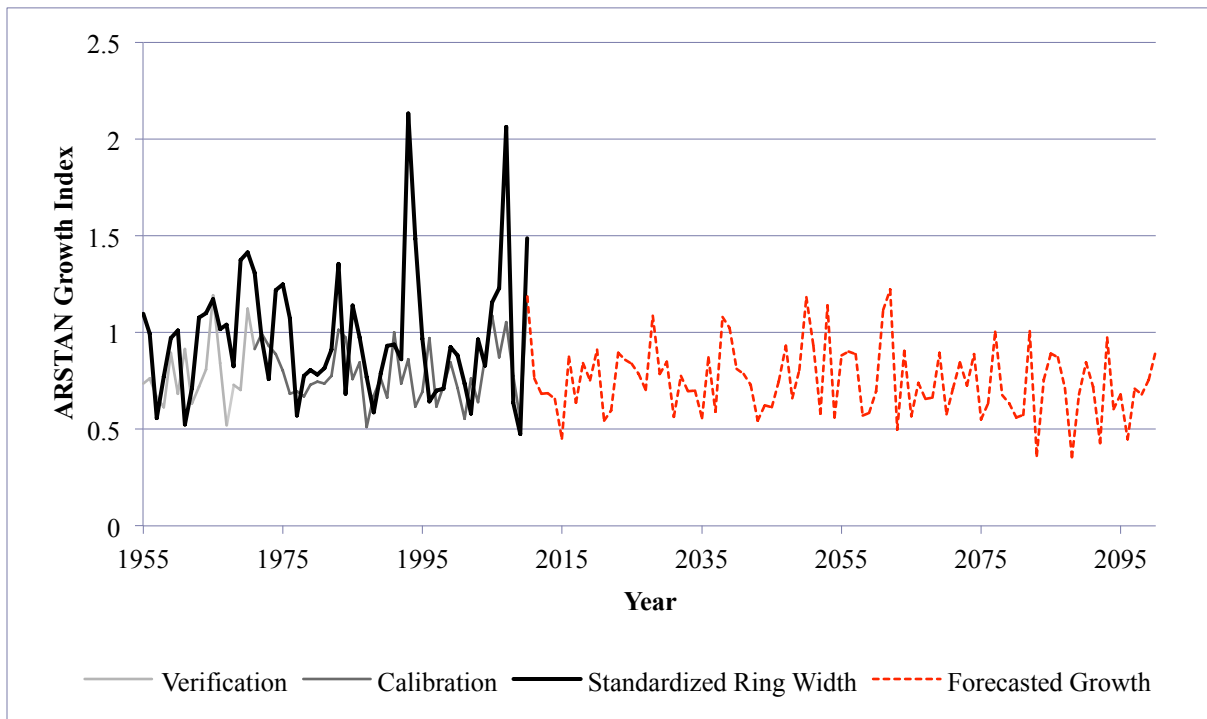
### **Acute Willow**

The selected future-growth model for acute willow includes three climate variables (Table 2.2). Two of the variables (previous September precipitation and June precipitation) were revealed in an earlier climate analysis as two of the most significant climate variables for the growth of this species (Figure 1.4).

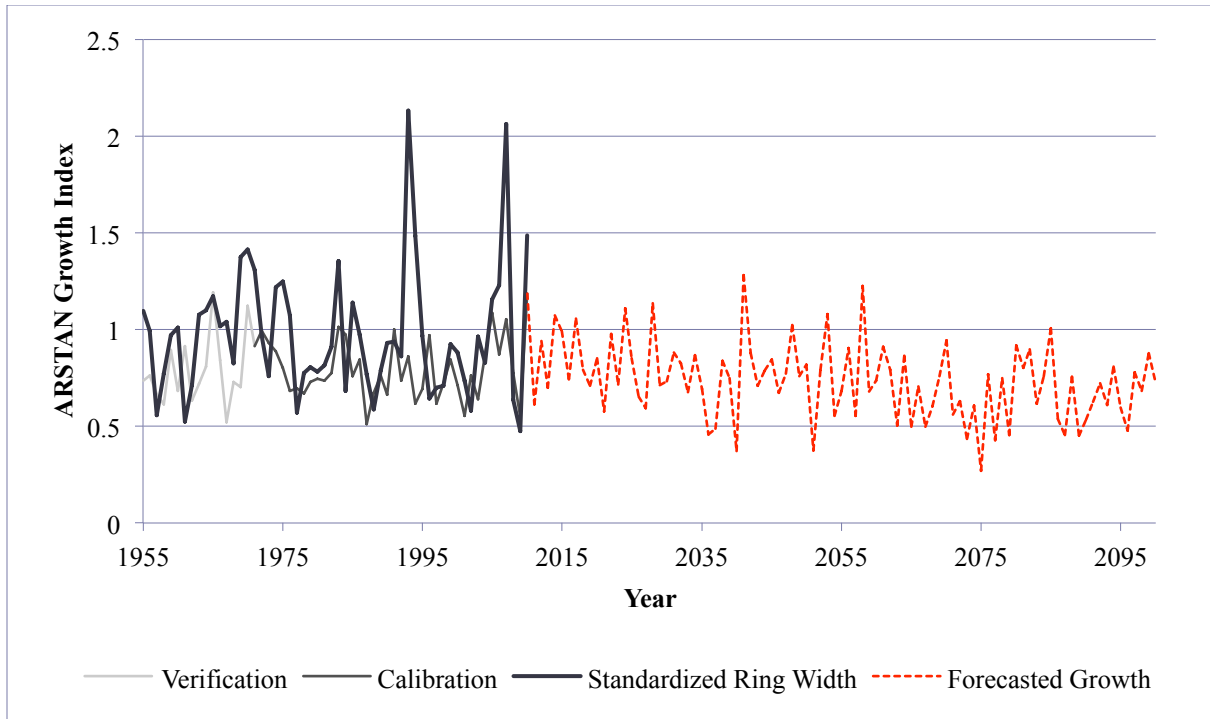
**Table 2.2** Model variables used for future growth forecasting – acute willow

Model Variables	Unstandardized Values
(Constant)	1.177581
Previous September Precipitation	0.007026
Current June Precipitation	0.003072
Current September Precipitation	-0.059387

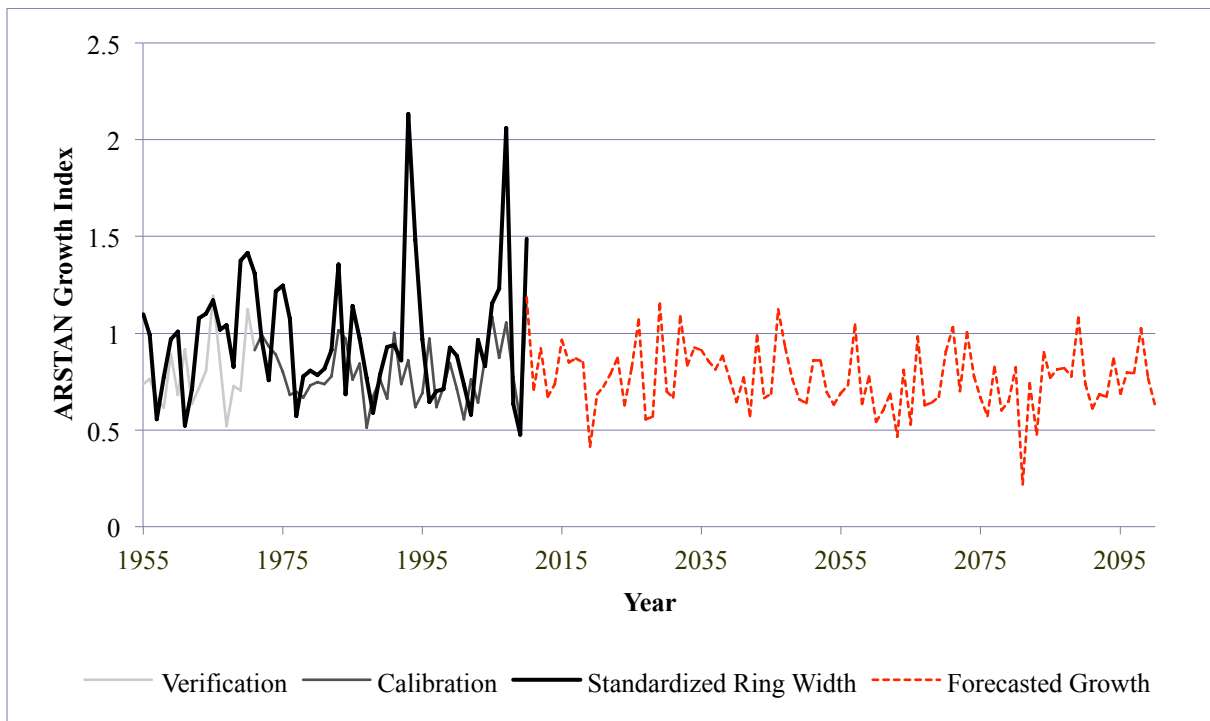
The standardized radial-growth of acute willow appears to be slightly suppressed under future climate scenarios, particularly in scenario A2 (Figure 3a-c). The earlier DendroClim analysis reveals that acute willow, in general, correlates negatively with temperature, and positively with precipitation. Based on the established criteria, the forecasted median growth values suggest that acute willow will experience moderately suppressed growth under all three future climate scenarios, as they are projected to be within +/- 11-20% of their historical mean.



**Figure 2.3a** Future growth of acute willow modeled using SRES A1b



**Figure 3b** Future growth of acute willow modeled using SRES A2



**Figure 2.3c** Future growth of acute willow modeled using SRES B1

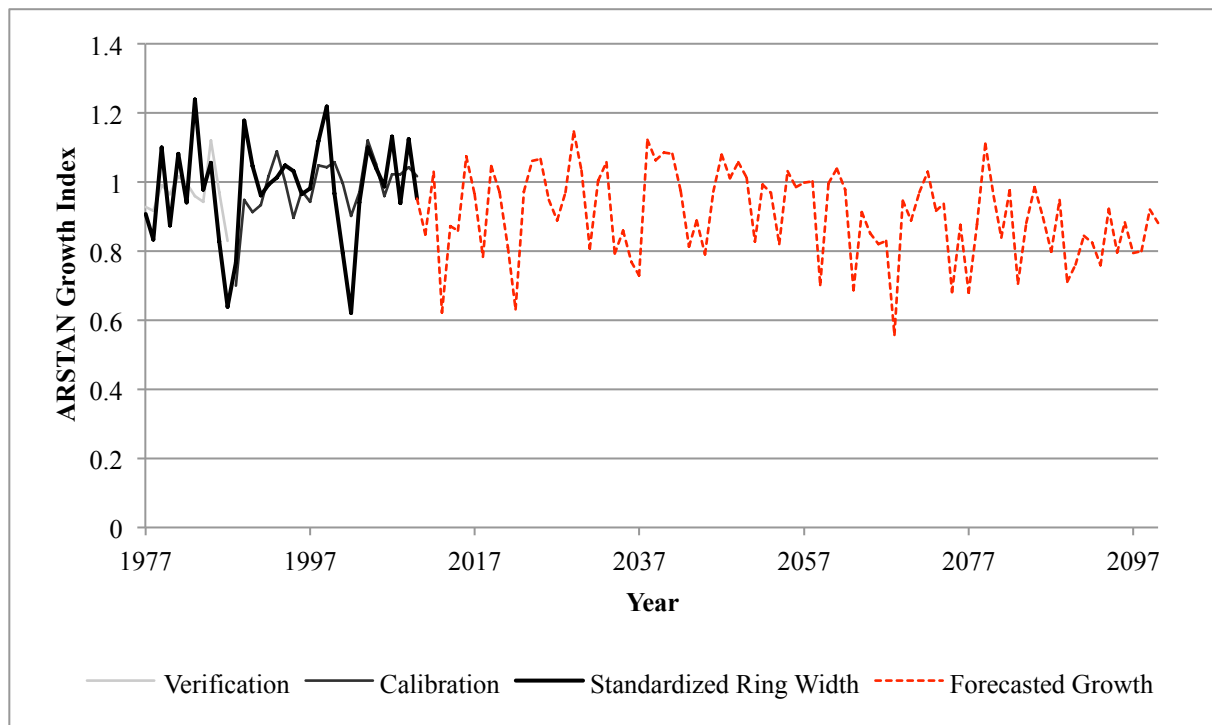
## Caragana

The future growth models of the shrub species caragana suggest that it will experience stable growth under a warmer and drier climate. This is likely due to the high drought tolerance of this species.

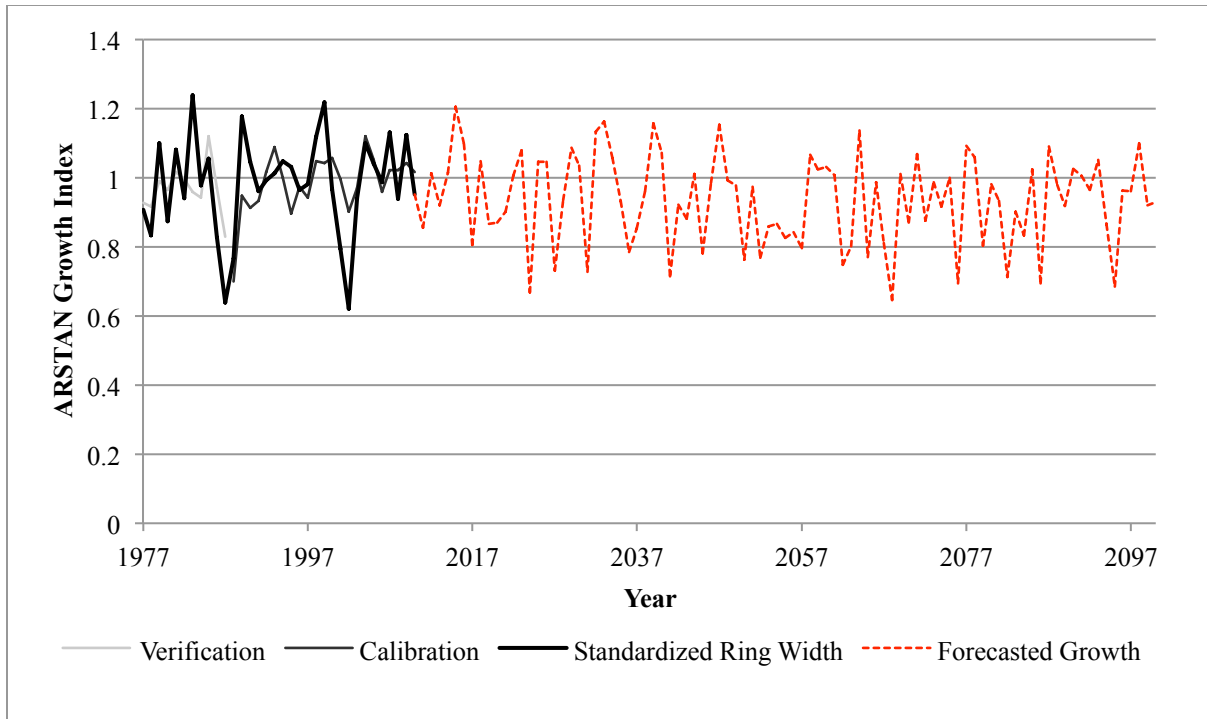
The climate variable of the most importance for this species is undoubtedly June temperature of the current year. Future growth models were successful in explaining 26.94% of variance during the calibration period, and 39.38% during the verification period (the highest explanatory power of all). While these results are promising for further growth modeling, it is important to note that the length of the chronology was relatively short compared to the rest of the species studied.

**Table 2.3** Model variables used for future growth forecasting – caragana

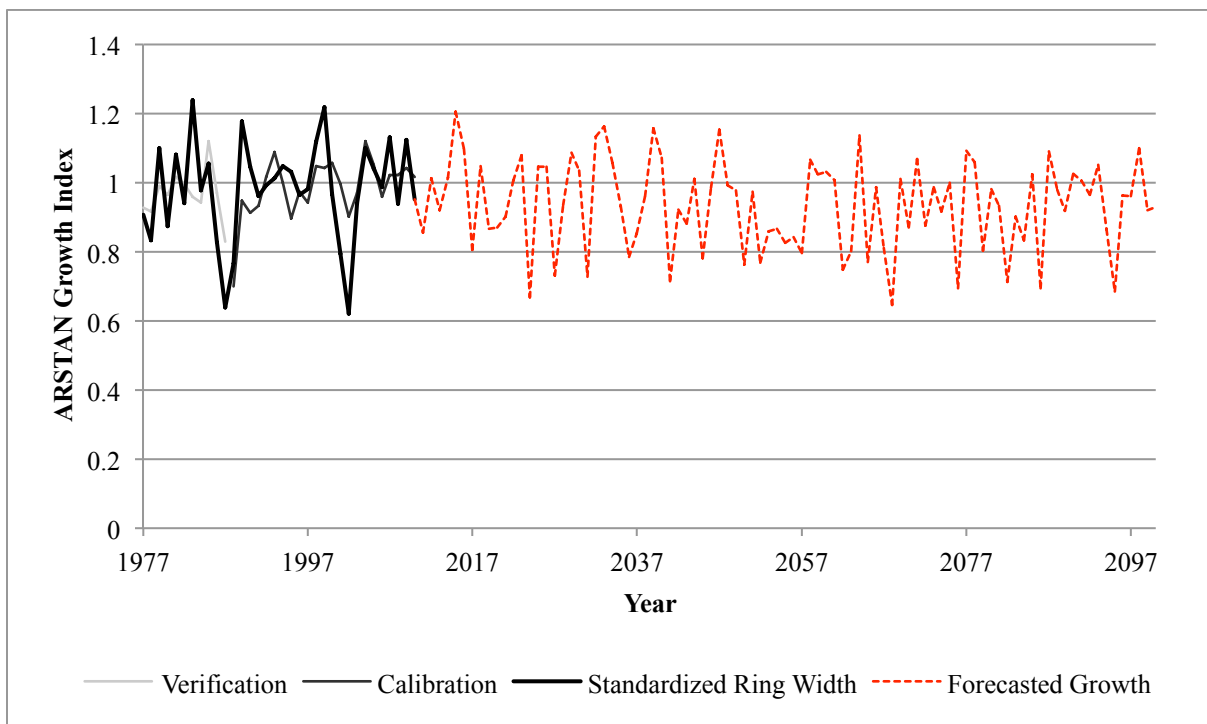
Model Variables	Unstandardized Values
(Constant)	1.812
Current June Temperature	-0.520



**Figure 2.4a** Future growth of Caragana modeled using SRES A1b



**Figure .4b** Future growth of Caragana modeled using SRES A2



**Figure 2.4c** Future growth of Caragana modeled using SRES B1

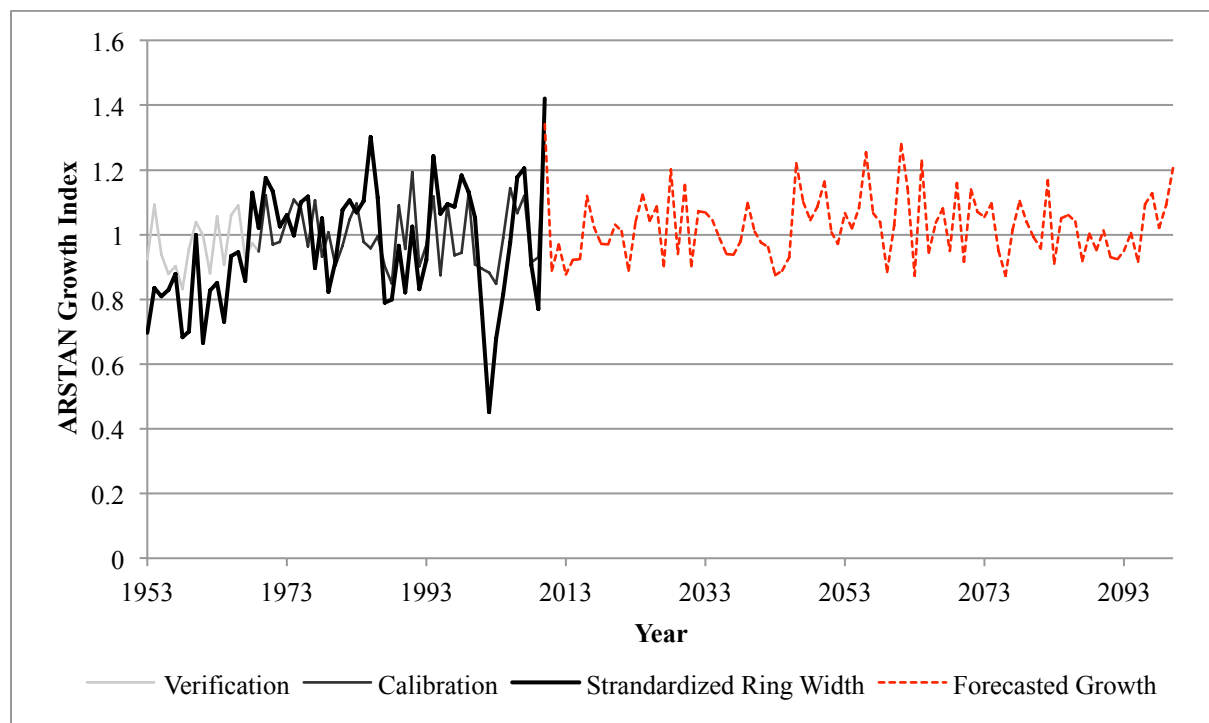
## Colorado Spruce

The model of best fit for Colorado spruce uses two variables to forecast future growth (Table 2.4). May and June precipitation explain the greatest amount of annual variation in tree-ring growth, something that is confirmed by the earlier DendroClim Analysis (Figure 1.4).

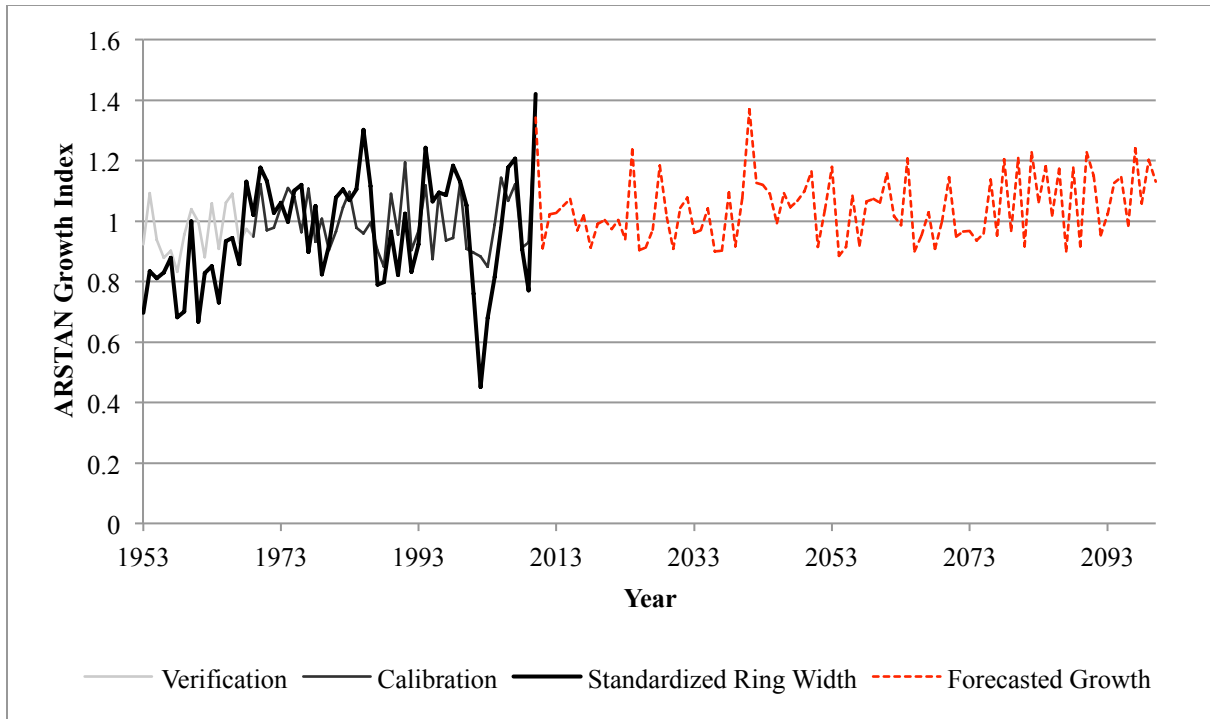
**Table 2.4** Model variables selected for future growth forecasting, Colorado spruce

Model Variables	Unstandardized Values
(Constant)	0.773054
Current June Precipitation	0.001893
Current May Precipitation	0.001939

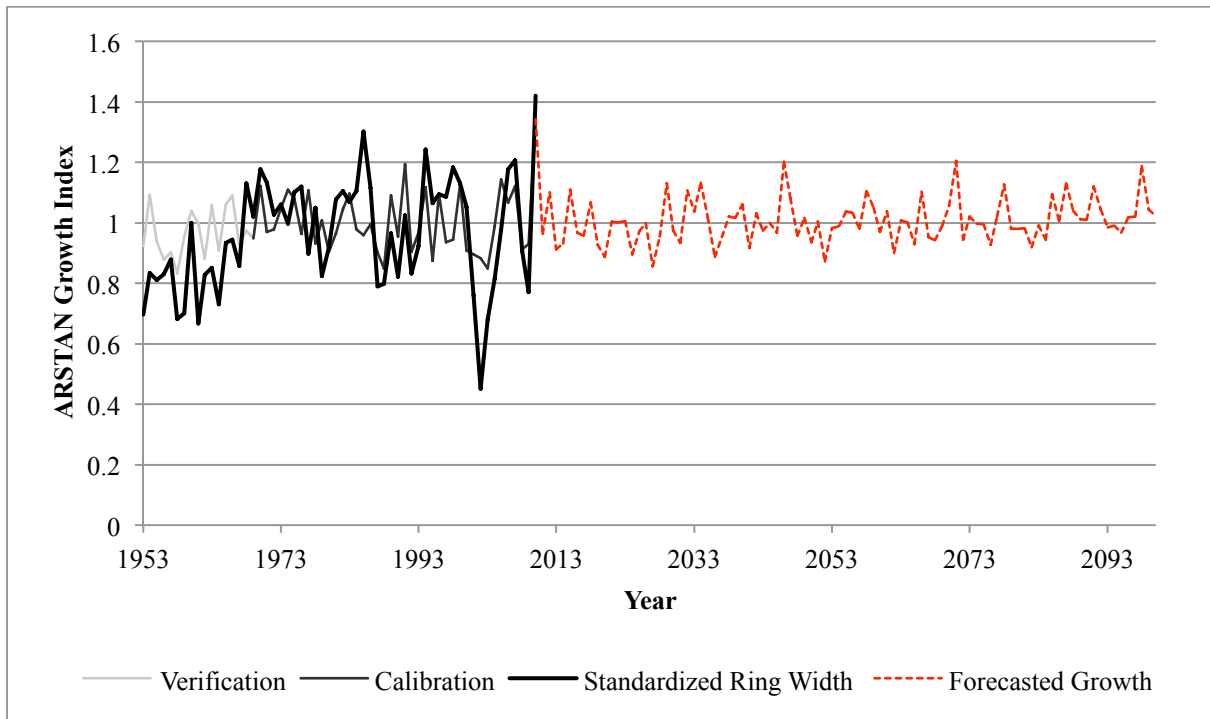
Correlation values reveal that the modeled calibration period explains 33.41% of annual variability, while the verification period explains 15.00%. Based on the generated models (Figs. 2.5a-c), the median forecasted growth values suggest that Colorado spruce will experience stable growth under SRES A1b, A2, and B1 scenarios.



**Figure 2.5a** Future growth of Colorado spruce modeled using SRES A1b



**Figure 2.5b** Future growth of Colorado spruce modeled using SRES A2



**Figure 2.5c** Future growth of Colorado spruce modeled using SRES B1

## Green Ash

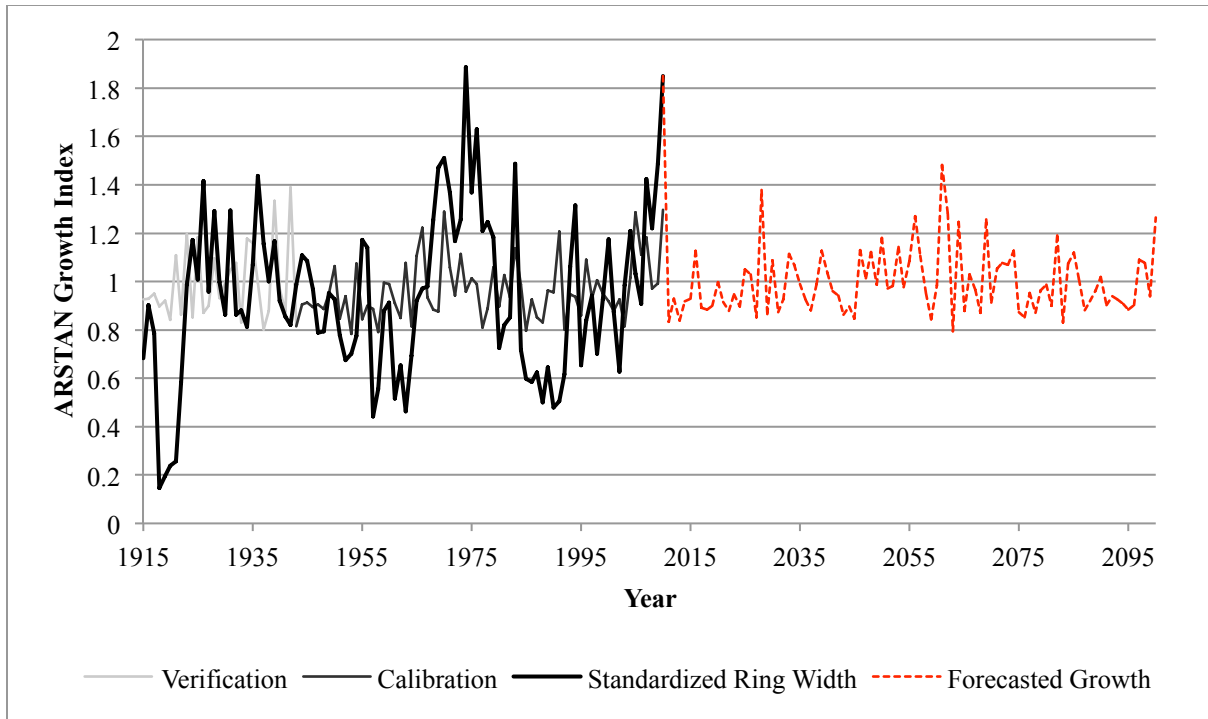
A previous climate analysis has demonstrated that green ash is a relatively complacent species in the Canadian Prairies, with June climate variables dominating the climate's influence (Figure 1.4). Only 15% of the annual variability is explained by the three most significant climate factors (Table 1.2).

**Table 2.5** Model variables selected for future growth forecasting, green ash

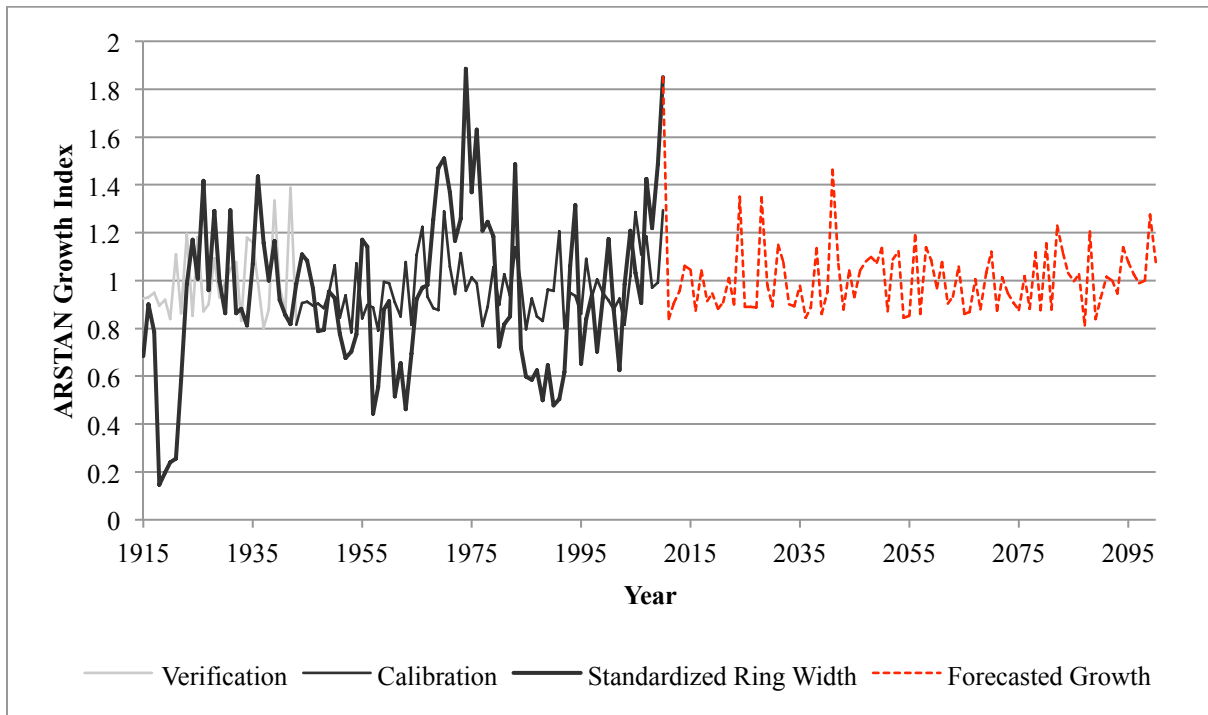
<b>Model Variables</b>	<b>Unstandardized Values</b>
(Constant)	0.747113
Current June Precipitation	0.003244

The models for green ash confirm its complacency under future climate scenarios (Figs. 2.6a-c). The mean growth values suggest that green ash will exhibit stable growth and is likely to continue its current trajectory well into the future.

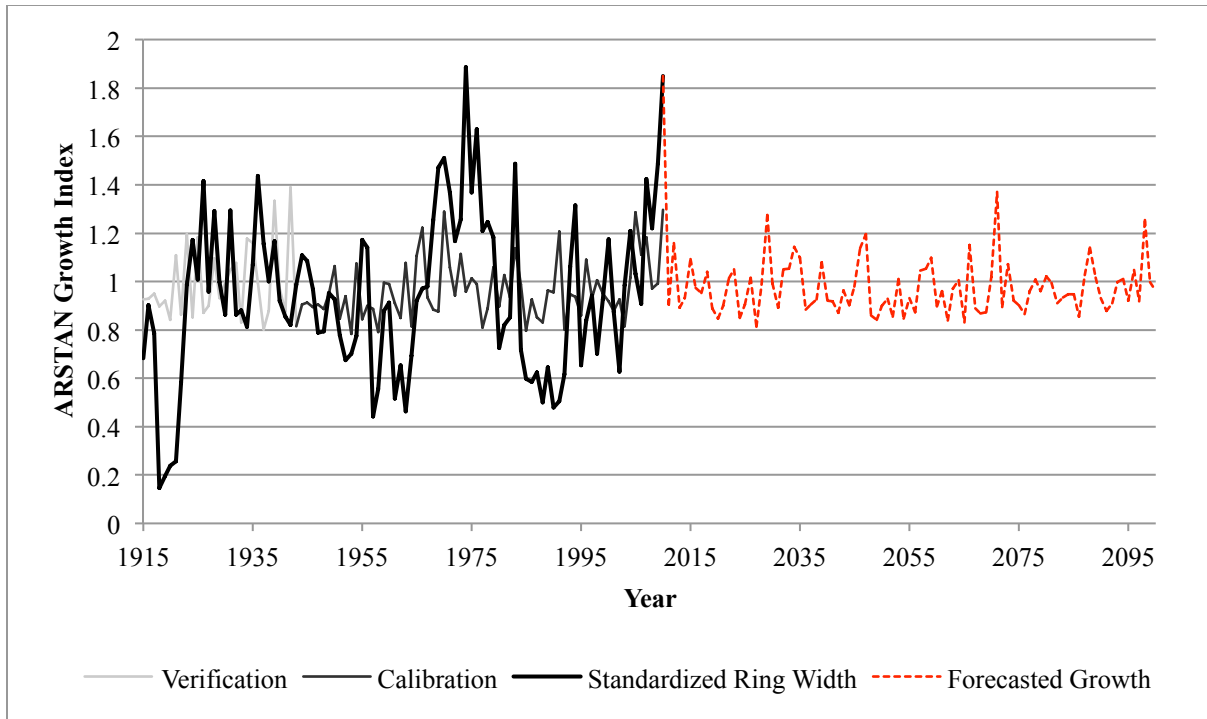
The model calibration period for green ash explains 13.25% of the annual variability in tree-ring growth, while the verification period explains only 1.80%. The low explanatory power of the model is clear in the graphical representations (Figures 2.6a-c), where the extreme values are not well represented in either the calibration or verification period.



**Figure 2.6a** Future growth of green ash modeled using SRES A1b



**Figure 2.6b** Future growth of green ash modeled using SRES A2



**Figure 2.6c** Future growth of green ash modeled using SRES B1

### Hybrid Poplar

The future growth of hybrid poplar is likely to decrease significantly from current levels. The future growth model encompasses four climate variables (Table 2.6), and hybrid poplar appears to be the only species significantly influenced by overall winter precipitation.

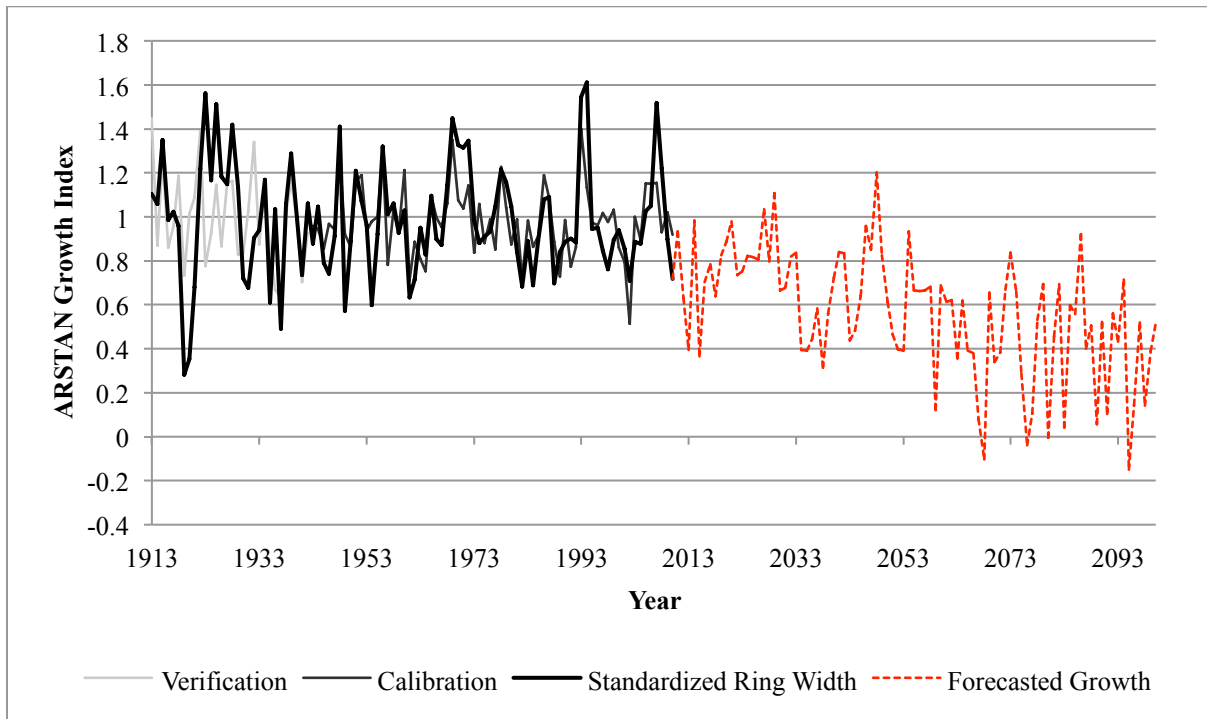
**Table 2.6** Model variables selected for future growth forecasting, hybrid poplar

Model Variables	Unstandardized Values
(Constant)	3.121363
Previous September Precipitation	0.005253
Current July Temperature	-0.094994
Previous August Temperature	-0.040693
Winter Precipitation	0.001269

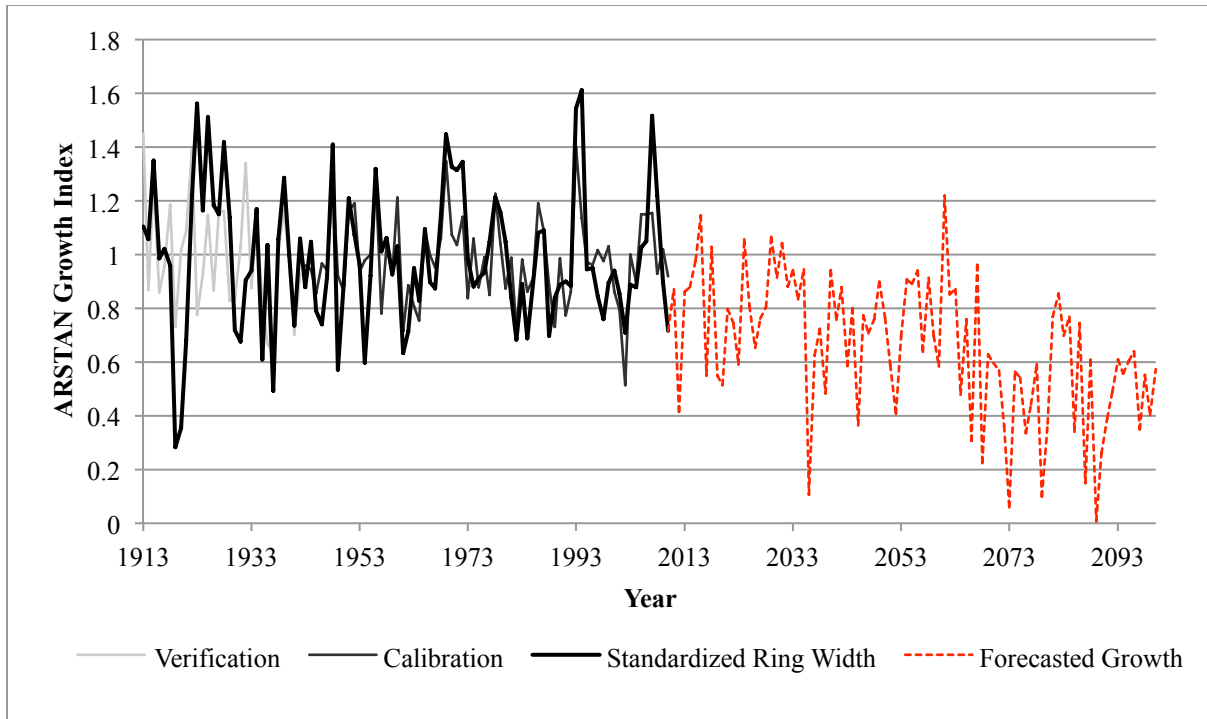
The model verification period explained 14.51% of the annual variation in growth, while the model calibration described 49.84%. Although previous analyses demonstrated hybrid

popular was only of intermediate usefulness for dendrochronology (usefulness rank = 6, Table 1.4), hybrid poplar seems to work relatively well for radial growth forecasting.

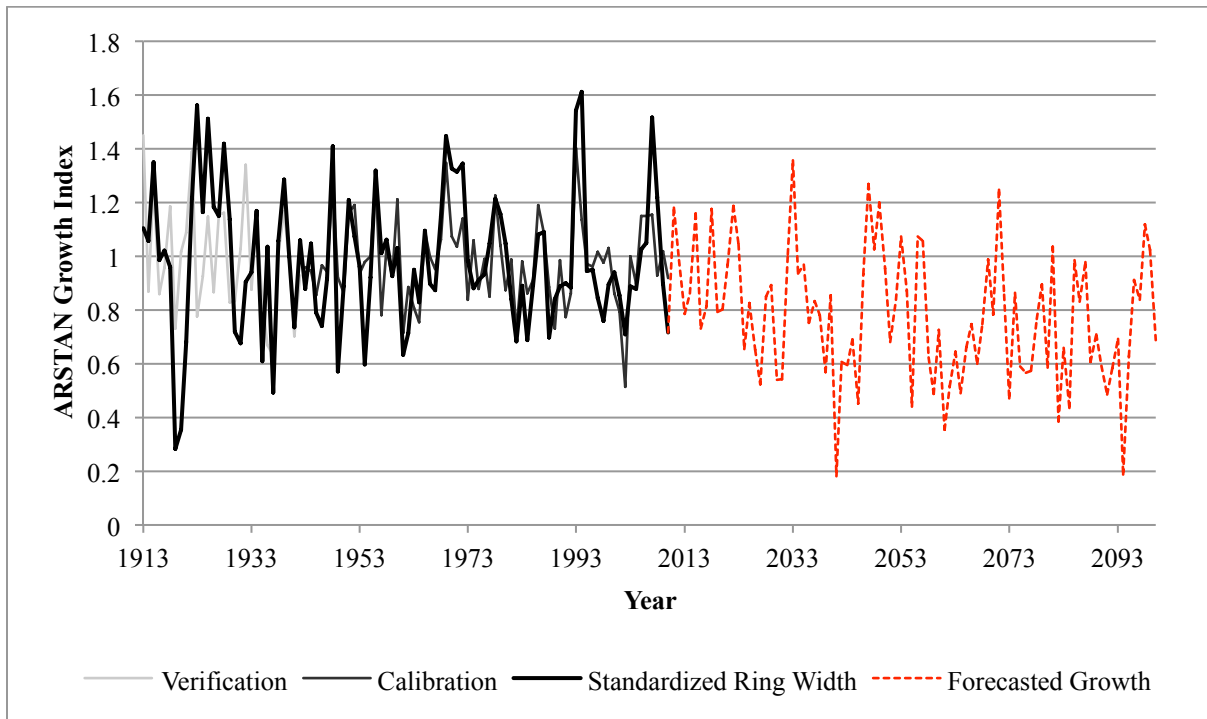
The future growth models depicted for hybrid poplar in Figures 2.7a-c demonstrate that this species will not grow well under future climate scenarios. A continuous suppression in radial growth becomes apparent when comparing mean historical growth values to those predicted for the future. The forecasted median growth of hybrid poplar is classified as being extremely suppressed based on previously established criteria. This indicates that hybrid poplar will respond poorly to increased mean temperatures in the future, an idea supported by earlier climate analyses that demonstrate the growth of hybrid poplar being negatively correlated with mean monthly temperature (Figure 1.4).



**Figure 2.7a** Future growth of hybrid poplar modeled using SRES A1b



**Figure 2.7b** Future growth of hybrid poplar modeled using SRES A2



**Figure 2.7c** Future growth of hybrid poplar modeled using SRES B1

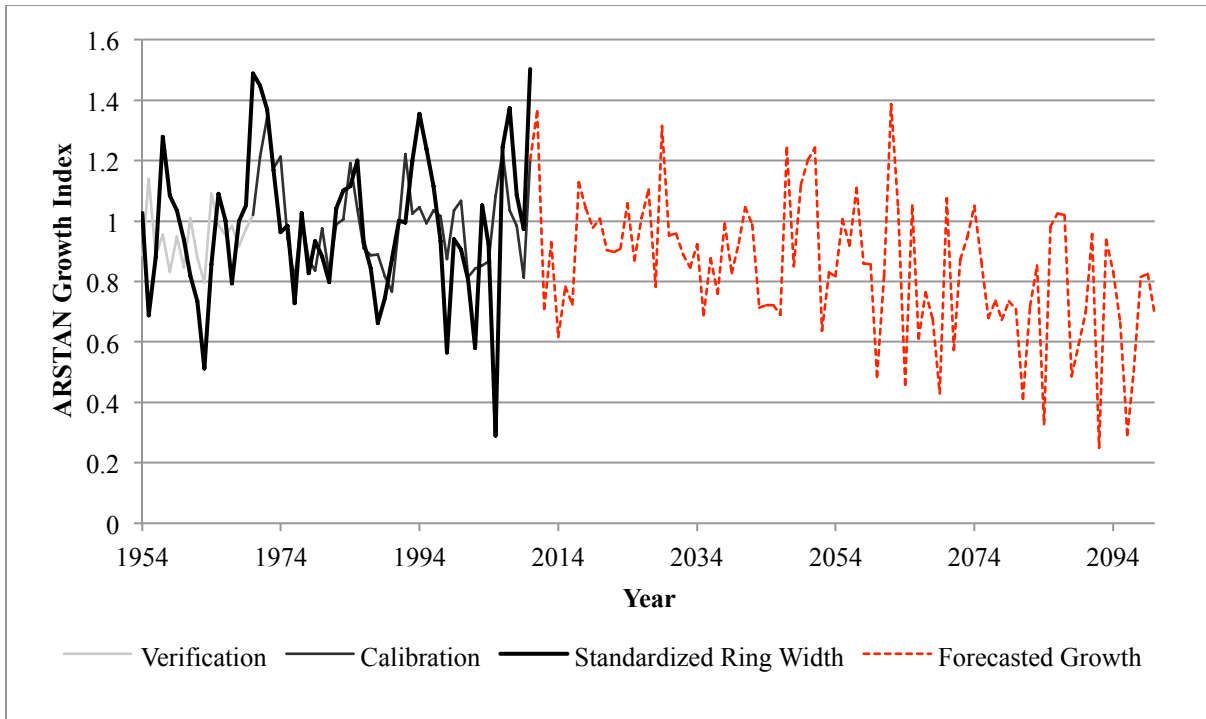
## Manitoba Maple

The future growth of Manitoba Maple is modeled using three climate variables, including two from the previous year (Table 2.7). Based on the variable coefficients, it appears as though Manitoba Maple responds negatively to increased temperature.

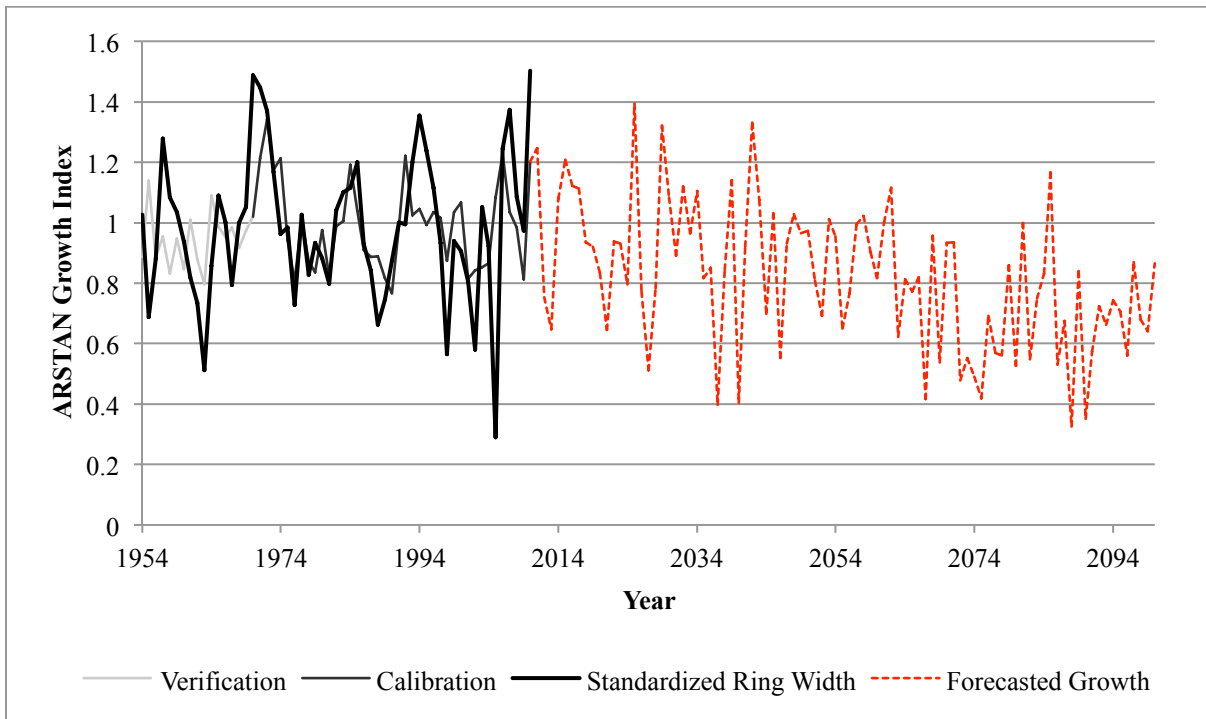
**Table 2.7** Model variables selected for future growth forecasting, Manitoba maple

Model Variables	Unstandardized Values
(Constant)	2.387162
Current September Temperature	-0.045300
Previous June Precipitation	0.002386
Previous July Temperature	-0.056335

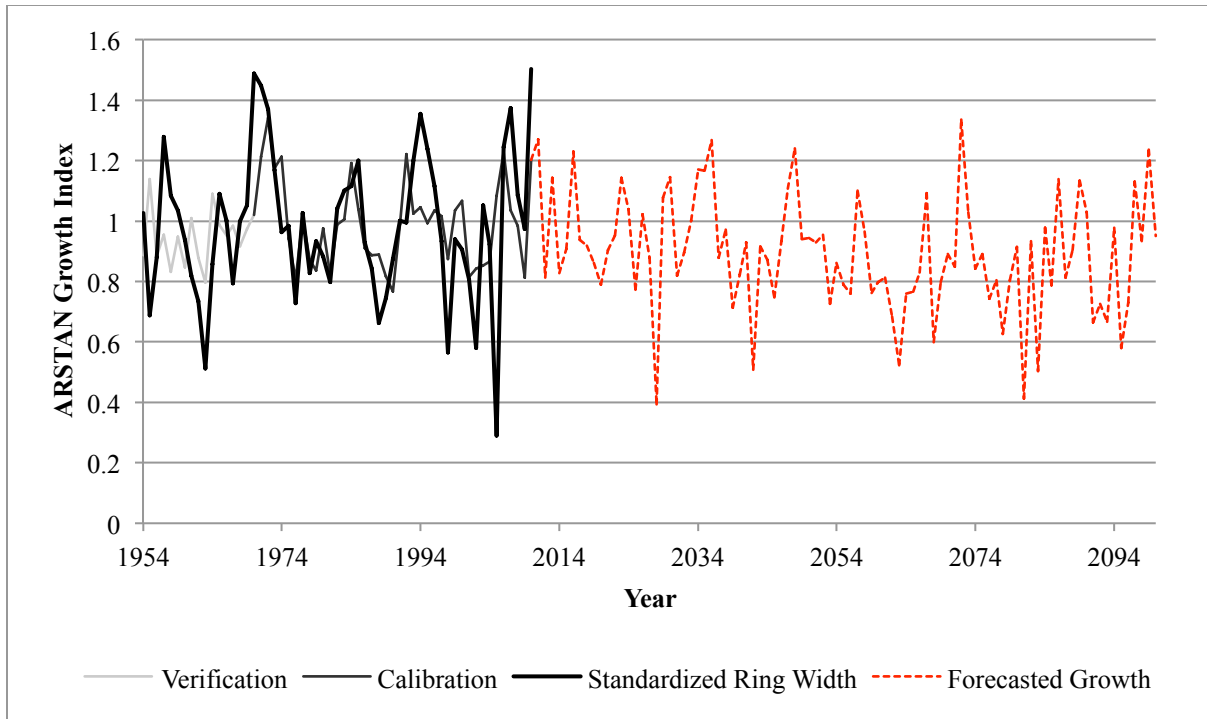
The predicted future growth of Manitoba maple is moderately suppressed under the three climate scenarios (Figures 2.8a-c), exhibiting between +/- 11-20% departures from the historical standardized growth value. The multilinear-regression model selected for forecasting future growth explains little variability in the verification period (explaining only 1.25% of the annual variance). The model appears to improve during the calibration period, accounting for 33.52% of the variability.



**Figure 2.8a** Future growth of Manitoba maple modeled using SRES A1b



**Figure 2.8b** Future growth of Manitoba maple modeled using SRES A2



**Figure 2.8c** Future growth of Manitoba maple modeled using SRES B1

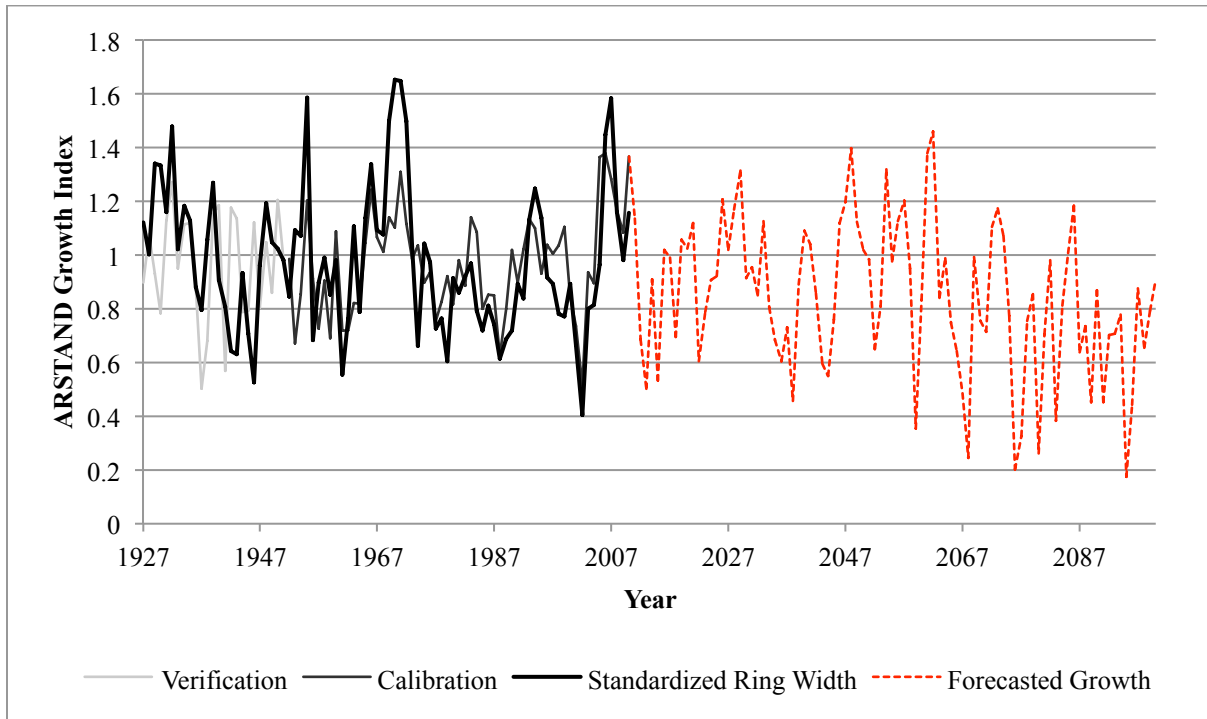
### Scots Pine

Based on the model variables, it appears as though Scots pine is largely driven by precipitation (Table 2.8), with the selected model incorporating five precipitation variables. The future growth model had relatively low explanatory power for the verification period (3.13% explained variability), but a much more acceptable 45.56% explained variance for the calibration period.

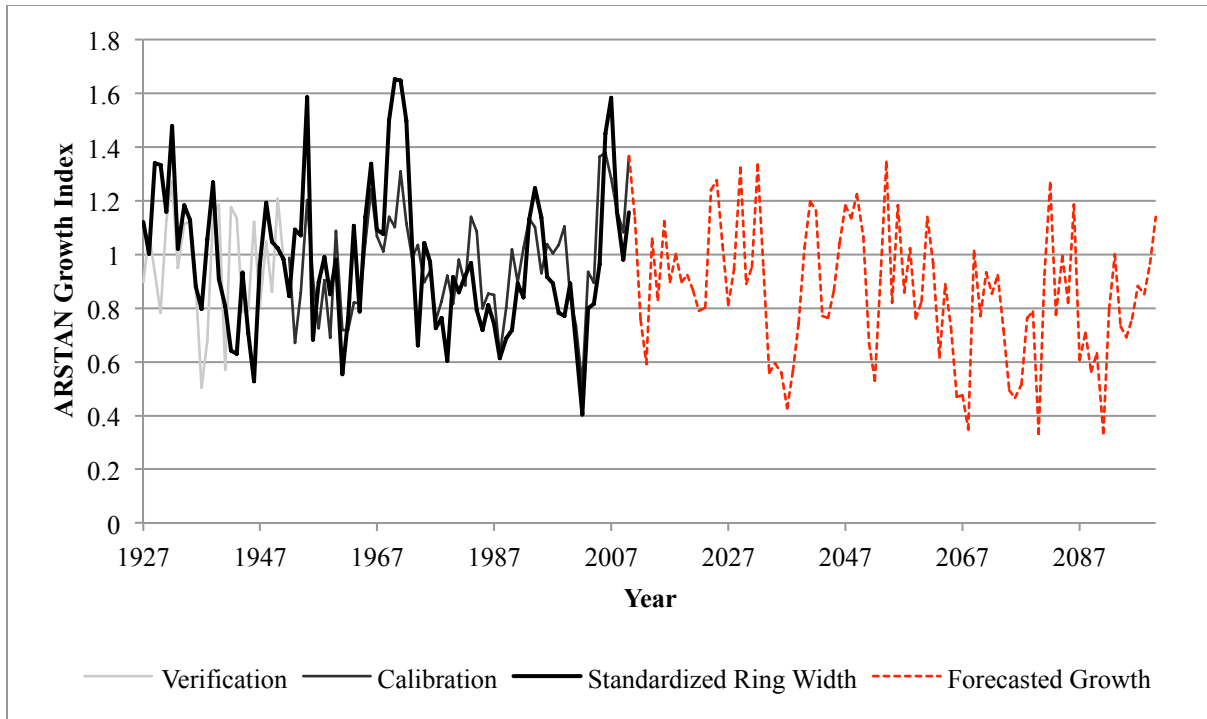
**Table 2.8** Model variables selected for future growth forecasting, Scots pine

Model Variables	Unstandardized Values
(Constant)	1.860059
Current June Precipitation	0.002315
Previous June Precipitation	0.002723
Previous August Precipitation	0.003107
Current July Precipitation	-0.080686
Previous September Precipitation	0.003514

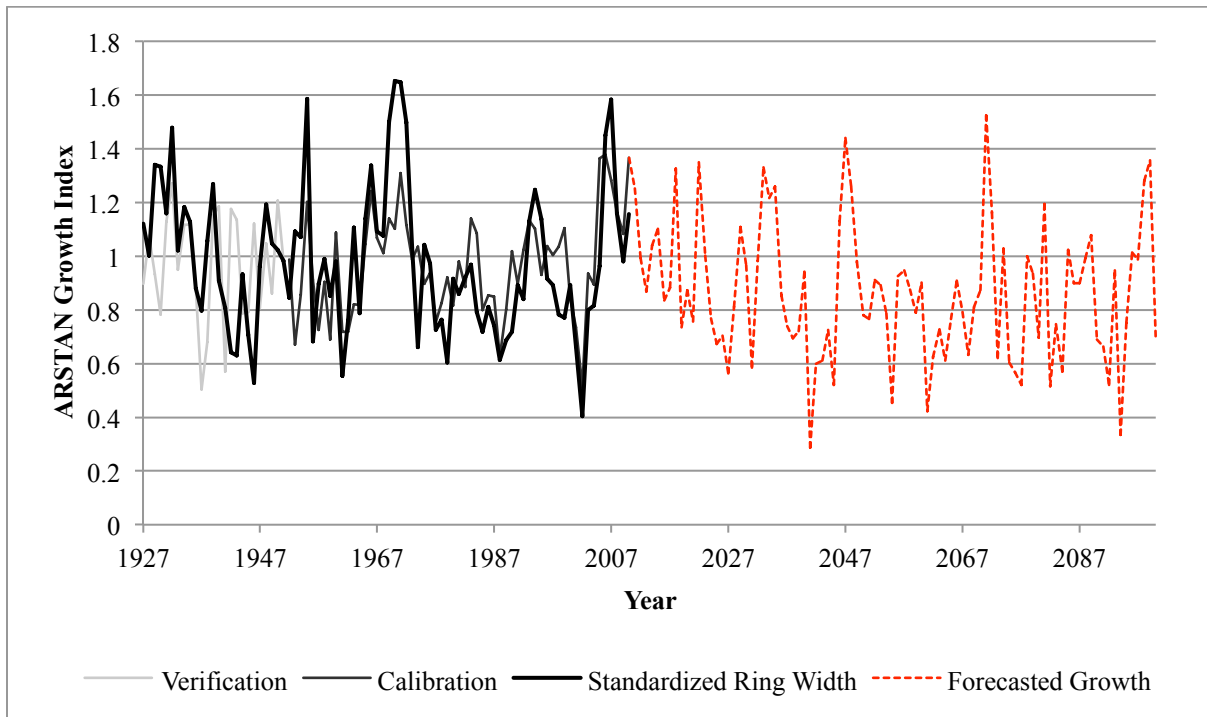
The future growth forecasts for Scots pine indicate a moderate level of growth suppression under future climate scenarios. This may be a result of increasing temperatures that could alter the moisture balance, as mean amounts of precipitation appear to increase only slightly in future climate scenarios (Figure 2.2).



**Figure 2.9a** Future growth of Scots pine modeled using SRES A1b



**Figure 2.9b** Future growth of Scots pine modeled using SRES A2



**Figure 2.9c** Future growth of Scots pine modeled using SRES B1

## Siberian Elm

Of the nine shelterbelt species analyzed, Siberian elm was the only one whose future growth could not be modeled using the established methods. This is likely due to the fact that no single or combination of environmental parameters has a significant enough effect on annual growth to pass the F critical value of 0.15. This idea was verified by further attempts in modeling using a higher F critical value, at which point a model was created (albeit a weak one). That Siberian elm does not work for future growth forecasting fits in with the fact that it was ranked as the second least useful species for dendrochronology based on previous analyses (Table 1.4).

## White Spruce

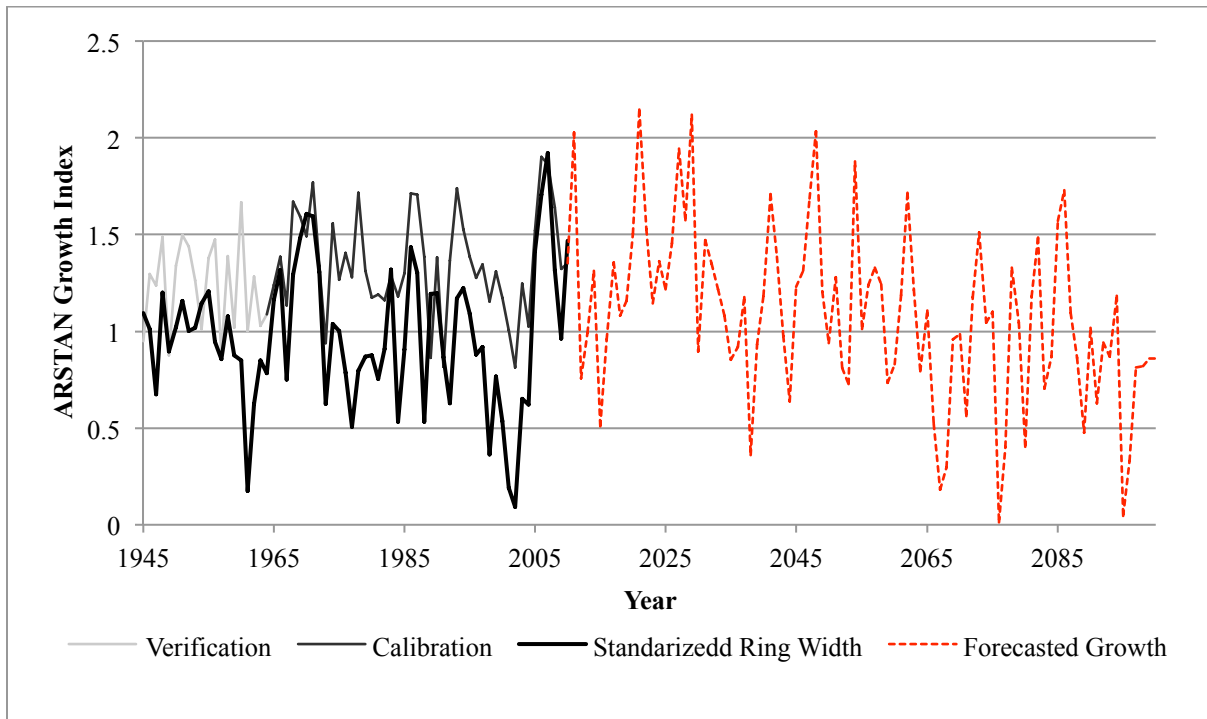
The future growth model for white spruce incorporates seven temperature and precipitation variables. The model explains an intermediate amount of variability during the verification period relative to the other species studied (10.50%), but accounts for 66.42% percent of the annual variability in growth during the calibration period, which is approximately 17% higher than the next closest species (hybrid poplar).

**Table 2.9** Model variables selected for future growth forecasting, white spruce

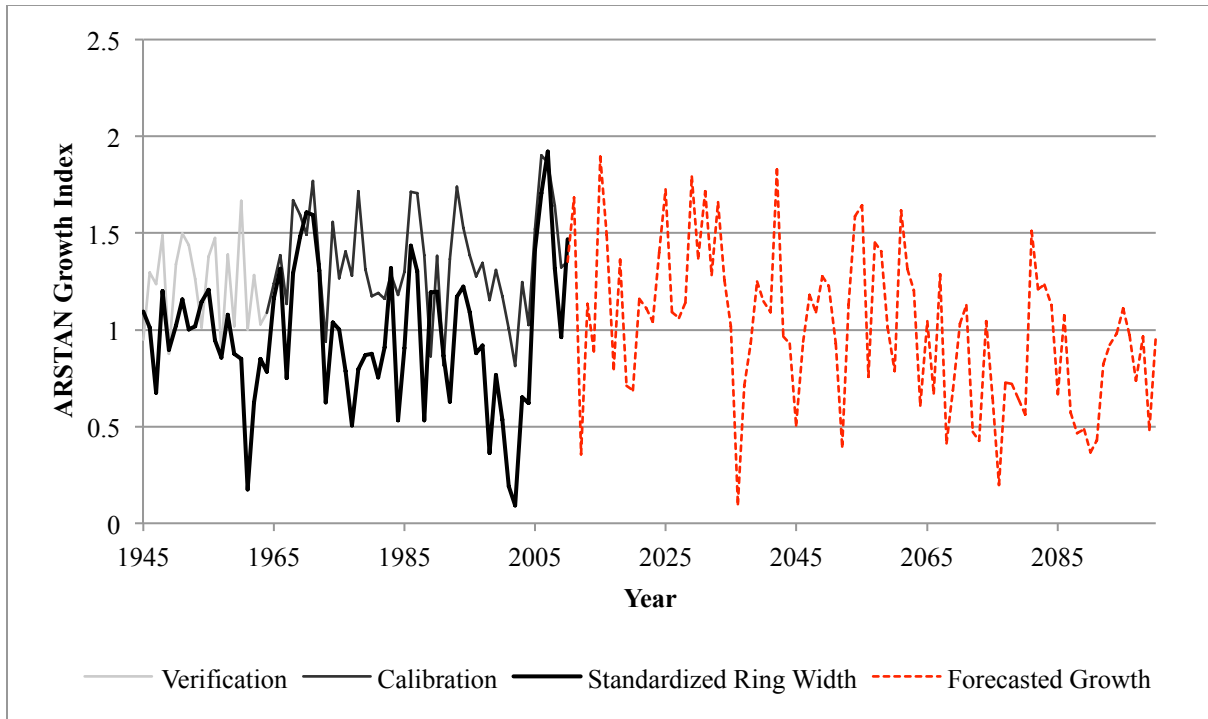
<b>Model Variables</b>	<b>Unstandardized Values</b>
(Constant)	3.298652
Current June Precipitation	0.004224
Previous September Precipitation	0.009830
Current July Temperature	-0.082861
Current July Precipitation	0.004221
Previous August Temperature	-0.066874
Previous June Precipitation	0.003164
Current August Temperature	-0.043969

Upon visual inspection of Figures 2.11a-c, it is apparent that while the calibration period captures much of the annual variability in tree-ring growth, the magnitude of the variability appears to be inaccurate.

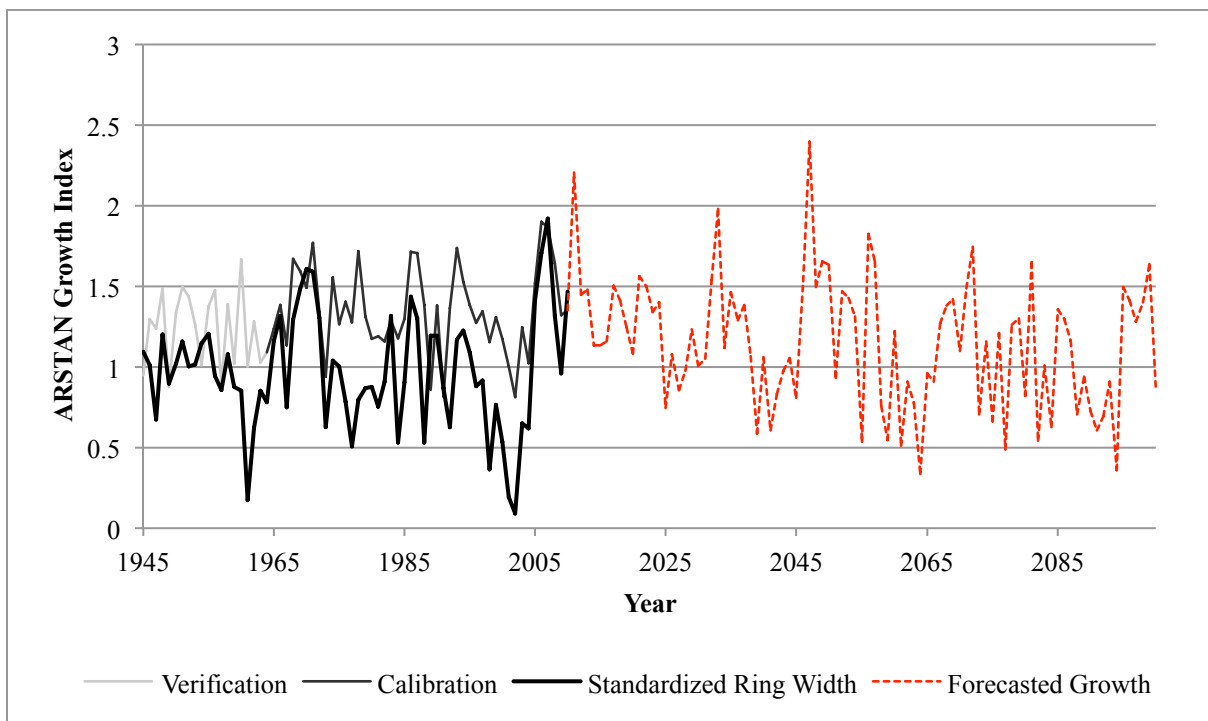
Future growth forecasts suggest that white spruce will not be greatly affected by future changes in climate. Responses in radial growth for SRES A1b and A2 indicate a stable level of future growth, while B1 indicates a moderate increase.



**Figure 2.10a** Future growth of white spruce modeled using SRES A1b



**Figure 10b** Future growth of white spruce modeled using SRES A2



**Figure 2.10c** Future growth of white spruce modeled using SRES B1

The median future growth trends for the nine species reveal that most will experience moderately suppressed or stable growth under the three future climate scenarios (Table 2.11). Hybrid poplar is likely to experience extremely suppressed growth, and white spruce may experience a moderate increase in growth with SRES B1. It is also notable that besides white spruce, all species respond to the three climate scenarios in a similar manner (i.e. all SRES produce the same future growth classification).

**Table 2.10** Median future growth trends for SRES A1b, A2, and B1

<b>Species</b>	<b>Future Growth Trend</b>
Acute willow	Moderately Suppressed
Caragana	Stable Growth
Colorado spruce	Stable Growth
Green ash	Stable Growth
Hybrid poplar	Extremely Suppressed
Manitoba maple	Moderately Suppressed
Scots pine	Moderately Suppressed
Siberian elm	-
White spruce	Stable Growth (A1b, A2), Moderate Increase (B1)

## **Discussion**

By classifying future growth trends qualitatively, we are able to compensate for some of the uncertainty surrounding future growth modeling. The findings of our analysis demonstrate that most shelterbelt species will experience either stable or moderately suppressed growth under three future climate scenarios. This suggests that some species will experience more favorable growth than others as the Prairie climate changes, which has implications for the amount of carbon that can be stored in each tree or shrub.

Radial-growth forecasting is riddled with sources of uncertainty, and there is a risk of error being compounded with each additional step in the analysis. This being the case, it should be kept in mind that while each growth model reveals a different pattern of future growth, there

are many different specific methods of modeling, each producing a slightly different result. Future growth models should be valued for their overall directions of projections rather than specific output values for each year.

The  $R^2$  values for the verification periods of each species were relatively low. This suggests that only some of the annual variability in historical tree-ring growth was captured by the models produced in the multilinear regression. Future endeavors in radial-growth forecasting should, therefore, attempt to produce models with a greater variety of climate variables. This exercise used only the most basic environmental variables (temperature, precipitation, and winter precipitation) to model future growth, many of which are indirect indicators of what actually influences the growth of trees and shrubs. An example of this is using a monthly temperature variable, while it may in fact be the level of sunlight that is truly driving photosynthesis and subsequent radial growth. A further methodological change that could be beneficial would be to establish an alternative method to select the years used in the verification and calibration periods.

## **Conclusion**

Future radial growth forecasting suggests that certain species will respond more favorably than others to future changes in climate in the Canadian Prairies. This has important implications for the many landowners who take part in shelterbelt planting each spring. By knowing which species will grow most favorably, landowners are able to make decisions as to which species to plant on their properties that will thrive in the future (or at least will not be negatively impacted by climate change). Additionally, by selecting species that will sequester a large amount of carbon, there may be a potential to use shelterbelt trees as carbon credits as a way of off-setting a portion of the greenhouse gas emissions associated with agricultural activity.

Based on our analysis, it appears as though caragana, Colorado spruce, green ash, and white spruce are the species that will experience the most favorable growing conditions in the future. These species seem to be either not likely to be affected by changes in climate, or else respond favorably to increased temperatures (Table 2.11). The annual-radial growth of acute willow, Manitoba maple, and Scots pine is likely to be negatively impacted by changes in climate based on our analyses. Hybrid poplar, because of its highly suppressed future growth

trend, should be avoided. This analysis revealed little of the future growth outcomes of Siberian elm.

### **Acknowledgements**

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