Reducing Uncertainty:

Acadian Forest Radial Growth Forecasting at a Multi-level Scope

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Abstract

This report focuses on the broad scope component of this 2009 Fundy Model Forest radial growth forecasting project. Improvements to past radial growth forecasting methodology are put into practice with this project in an attempt to improve the certainty of the modeled forecasts. Individualized forecasts are produced using more site specific climate data. Model selection techniques are refined, as are the climate variable model inputs. Combining these methodological improvements with specific site characteristics derived from the New Brunswick Ecological Land Classification, more detailed information is provided to demonstrate how these forecasts might be implemented at the landscape level and where they may be more appropriately used.

The forecasts produced through this project have indicated yellow birch should suffer decreasing radial growth rates due to more turbulent transitions from winter to spring. Jack pine is forecast to potentially experience slightly decreased growth rates due to less summer precipitation and largetooth aspen is forecast to increase growth rates due to warmer spring temperatures.

Broad Scope Project Component

Introduction

The prospect of having advanced knowledge regarding the response of tree growth to various climate change forecasts has inspired researchers to build models of future radial tree growth (Laroque and Smith 2003, Goldblum and Rigg 2005, Phillips and Laroque 2007, Girardin et. al 2008, Phillips and Laroque 2008, Selig et. al 2009). We have previously authored two reports on the potential response of eight local tree species to climatic changes in southeastern New Brunswick (Phillips and Laroque 2007, 2008). As a continuation of this research we had proposed to assess three more tree species for future radial growth potential. These species included yellow birch, jack pine and white spruce. Evidence from climate envelop studies suggested the optimum climate for these species will migrate to the north under low to moderate climate change scenarios (McKenney et. al 2007). To assess whether the currently rooted trees will undergo radial growth changes in response to these climatic shifts we began a search for stands of mature trees of the specified species. These trees would provide the tree-ring samples required for an analysis of the past growth-climate relationship and the subsequent radial growth forecasts.

Following an exhaustive search, the species of white spruce could not be found in stands old enough to provide the samples necessary for the project. Due to past anthropogenic use of the typical white spruce habitat, all stands found were on abandoned farmer's fields and did not supply enough tree-rings to establish a statistically significant growth-climate relationship. Considering this species has also been significantly affected by several spruce budworm outbreaks in the past, it was imperative to acquire tree-ring samples well over 100 years of age to reach statistical reliability. Because this became impossible on the landscape level, an alteration in our overall plan had to occur.

During previous field work, stands of large toothed aspen of the appropriate age had been discovered making this species a prime candidate for inclusion in our current research. Since this species grows quickly, especially in areas of forest disturbance, we concluded that its future potential as a species of temporary infill following climate change related mortality of other species could be important and worthy of study. Therefore, this report outlines the results of radial growth forecasts of yellow birch, jack pine and large toothed aspen.

Study Area

Site Description

The Acadian Forest Region (AFR) is distinguished as a mixed wood transition zone between the more northerly coniferous dominated forest and the more southerly deciduous dominated forests (Loo and Ives 2003) (Figure 1). This forest zones covers a large portion of the eastern Canadian Maritime provinces between 43˚ and 48˚ N latitude and it extends into Quebec and the northern New England states (Loo and Ives 2003). Within this forest region, the smaller and centralized area of southeastern New Brunswick (SNB) was chosen as a representative region to study (Figure 1). SNB is located between 45˚ and 46˚ 60' N latitude and 63˚ 50' and 66˚ W longitude with an elevation which ranges from sea level to 450m asl (Loucks 1962). This area is covered by four distinct eco-regions as defined by the Ecological Land Classification of Southeastern New Brunswick (Power and Matson 1995). The combination of lowlands, uplands, coast, and valley landforms has resulted in the four eco-regions being representative of the physical characteristics found throughout the AFR. The climate varies over SNB as the influence of coastal waters, changing elevations, and continental air masses contribute to the relative differences. The number of growing degree days varies from 1500-1700 based on above 5°C rates and the May to September precipitation values vary from 400-500 mm (Dizikowski 1984, Clayden 2000). Below you will find individual site descriptions based on information contained in the New Brunswick Ecological Land Classification (NBELC) (Zelazny et. al 2003).

Slipp Farm (SF) – Aukpaque Ecodistrict

This site is situated at 110m elevation on private land. The tolerant hardwood stand of sugar maple, beech and yellow birch is uneven aged and contains vigorous beech regeneration. Many of the trees found on this site contain cavities used by local wildlife. The terrain is flat and rocky on the top section of the plateau but the tolerant hardwood stand extends down an east facing slope, both of which are well drained. Also on this site is a forest stand of largetooth aspen and red pine at a similar elevation but near the top of a steep rocky slope. This is true old growth largetooth aspen as the trees were upward of 150 years old. Limited logging has occurred on this site over long periods of history.

The Slipp Farm sample site is located on the edge of the warmest ecoregion of New Brunswick called the Grand Lake Lowlands. Due to the lag in heat transfer between the atmosphere and Grand Lake the length of the growing season is extended and the frost free period is longer than any other area in New Brunswick. This results in warmer falls and an early finish of the winter season. This ecodistrict is characterized as dry and partially rain shadowed. The Slipp Farm lies on the boundary between the Aukpaque Ecodistrict of the Grand Lake Lowlands Ecoregion and the Yoho Ecodistrict of the Valley Lowlands Ecoregion (Zelazny et. al 2003).

Fundy Park (FP) – Caledonia Ecodistrict

This site is situated at 300m elevation in Fundy National Park. This tolerant hardwood stand is composed of uneven aged sugar maple, yellow birch, beech and red spruce. Previous to the establishment of the park in 1948 the forests here were in high demand for spruce timber so it is unlikely this stand ever witnessed significant harvesting pressure. The slope was relatively flat here but maintained a slightly north facing aspect.

Geographically, this site is located within the Caledonia portion of the Central Uplands Ecoregion. This ecoregion's alternate ecodistricts are found in the northern part of New Brunswick but share similar traits with this high-elevation area. The climate here is cool and moist keeping forest fire activity to a minimum. The elevation here allows the Caledonia Plateau an escape from the cool Bay of Fundy waters in the growing season. Although the site is within the Caledonia Ecodistrict it needs to be understood that the boundary of the Fundy Coastal Ecoregion is not far off. The steep temperature gradients emanating off the Bay of Fundy most likely affect this sample site. The cool waters of the bay produce frequent fog days when in contact with warm humid summer air. This fog is hindered on its inland movement by the steep elevation of the Caledonia Uplands but it penetrates far enough inland to have some effect on this site. The slope of this site does face north but it is located on the south, windward side of the uplands where orthographic lifting is responsible for a high level of annual precipitation. There is a quick transition from the red spruce dominated coniferous forests in the Fundy Coastal Ecoregion to the tolerant hardwood stands common on the plateau area, describing the character of this site well (Zelazny et. al 2003).

Kent Hills (KH) – Caledonia Ecodistrict

This site is located at 354m elevation northeast of Fundy National Park on a relatively flat and moderately well drained site. It shares many similarities with the Fundy Park sample site except that it is farther inland and should be less influenced by the Bay of Fundy. The climate can be described as cool and moist (Zelazny etl al 2003).

Rockville Escarpment (RE) – Kingston Ecodistrict

This site is located at 120m elevation on a south facing rocky escarpment on Trout brook. The site is very well drained and supports a forest of mainly red and white pine with some jack pine and red oak. Located at the upper reaches of this ecodistrict, this site is warm and dry. To the south are the Caledonia highlands which offer protection from storms and create a partial rain shadow (Zelazny et. al 2003).

Negro Brook (NB) – Anagance Ecodistrict

This site is located at 195m along Negro Brook on a southwest facing slope. The site is moderately well drained and supports a mixed stand of red pine and largetooth aspen. Similar to the Rockville escarpment, this site is warm and dry as it too is in the rain shadow of the Caledonia Highlands (Zelazny et. al 2003). Sandy soils are common here and forest fires have played an historical role in tree distribution.

Portage Vale (PV) – Anagance Ecodistrict

This site is at 150m elevation on a steep southwest facing hill overlooking the Kennebecasis River. It is only approximately 15km from the Negro Brook site. Here the forest is a mix of jack pine, largetooth aspen and trembling aspen. The climate conditions here are no different than described in the Negro Brook specification.

Table 1. Sites where tree species were sampled.

Sample Sites	Yellow Birch	Jack Pine	Largetooth Aspen
Slipp Farm (SF)	Sampled		Sampled
Fundy Park (FP)	Sampled		
Kent Hills (KH)	Sampled		
Rockville Escarpment (RE)		Sampled	
Negro Brook (NB)			Sampled
Portage Vale (PV)		Sampled	Sampled

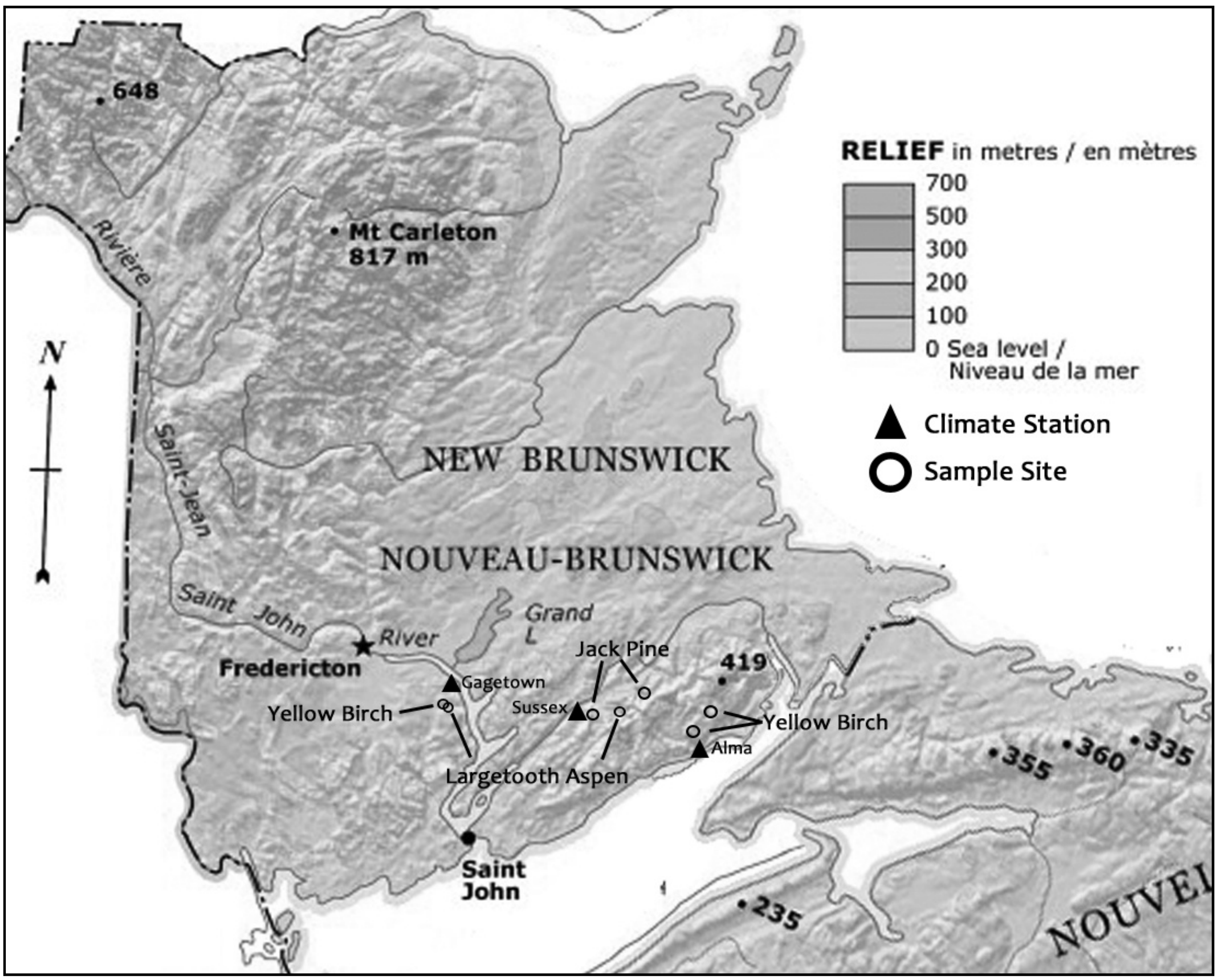

Figure 1. Map of the study region with specific species sampling sites indicated.

Methodology

Species Selection

The selection of species for inclusion in this study was based on the most abundant species located in the area with importance given to ecological conservation and forest resource use. Of the species considered, the tree types with evidence supporting their future demise were chosen. Sampling success further altered the final list of chosen species to yellow birch (Betula *alleghaniensis* Britt.), jack pine (Pinus *banksania* Lamb.) and largetooth aspen (Populus *grandidentata* Michx.). Figure 1 shows the locations of each sample site.

Climate Data

Weather data used for the analysis was derived from the Adjusted Historical Canadian Climate Data (AHCCD) website for Sussex, N.B. (station #8105200, length 1897-2005) (Vincent and Gullet 1999). Data sets produced for the narrow scope portion of this study were also used. A data set based on Gagetown, N.B. (station #8101800, length 1928-2002) and another based on Alma, N.B. (#8100200, length 1953-2002) were included in this portion of the study. For more information regarding the production of these data sets please see the methods section of the narrow scope portion of this project. Snow depth reconstruction data for these stations was accessed through the Canadian Daily Snow Depth Database Main Documentation (Brown and Braaten 1998).

The Third Generation Coupled Global Climate Model (CGCM3), produced by the Canadian Centre for Climate Modeling and Analysis, was used to derive the future weather data applied in the tree growth forecasts. Monthly data was calculated for the grid square covering the latitudes from 44°38'6.00"N to 47°26'42.00"N and longitudes from 63°17'6.00"W to 66°5'42.00"W.

Climate model Scenarios

This study takes a conservative approach to future climate model data. Data used is based on two scenarios from the Special Report on Emissions Standard (SRES) published by the IPCC (TGCIA 2007). The CGCM3 data used is based on the SRES B1 and SRES A1B scenarios. The B1 scenario is the low end estimate and assumes a 550ppm levelling off of CO_2 by the year 2100. The A1B scenario is an intermediate estimate and assumes a 720ppm levelling off of CO_2 by the year 2100.

Climate Model Data Calibration

The CGCM3 grid square covering the study site, from which the modeled data was derived, enveloped an area of 2.81° latitude by 2.81° longitude, including several distinct water bodies. This area is much larger than the study area and outputs an average homogenous result of temperature and precipitation over the entire heterogeneous zone, requiring a "change factor" conversion on the basic monthly resolution. This was possible because we had a baseline climatological record (i.e. Sussex historical weather data) and the calculations were relatively simple compared to a "statistical downscaling" approach (Diaz-Nieto and Wilby 2005). For each month of every year the CGCM3 data was subtracted from the point source Sussex data for the period 1900-2000. The resulting figures were then averaged for each month over the same period creating mean monthly divergence values. The divergence values were then added back onto the CGCM3 uniform data set to shift the magnitude of the values to that of the Sussex values and did not alter the variation of the data. The same divergence values were then applied to the future CGCM3 data adapting it to be representative for the future SNB climate. This process was also completed for the data sets from Gagetown and Alma.

Tree-ring Data

Tree-ring collections were made at three sites per species within the SNB region. At each site at least 40 core samples were taken from 20 trees using a 5.1mm increment boring tool. Sampling only occurred on sites where trees were over 100 hundred years old in order to maximize the potential temporal period over which a relationship could be established. Due to the difficulties in finding suitable sampling sites over 100-years old, other selection criteria such as, slope, aspect, elevation, substrate, and site separation often had to be ignored. The resulting tree-ring data was therefore a consequence of an opportunistic sampling strategy. Although micro-site characteristics were largely disregarded, individual tree species are most often found growing on similar terrain (Power and Matson 1995) and most sampling sites in this study shared similar characteristics.

In all, 9 sites were sampled meeting the three sites per species requirement. Increment cores were prepared using standard dendrochronological procedures (Stokes and Smiley 1968). Following preparation, all cores were visually cross-dated and then ring-widths were measured to 0.001 mm using either a VELMEX measuring system or a WINDENDRO™ scanning system. Statistical cross-dating of the measured ring width patterns was carried out through statistical evaluation with the program COFECHA (Grissino-Mayer 2001). On occasion, cores were found with poor correlation values identified through this procedure and they were eliminated. The remaining cores for each site were standardized to remove non-climatic, low frequency growth signals, such as age related trends and competition induced growth suppression. Using the program ARSTAN (Cook 1985), ring-width series were double detrended, first using a negative exponential curve or linear regression, then using a spline of 50% frequency response and indexed values for each chronology were created. Following detrending procedures the individual site chronologies were entered into correlation matrices with like species to determine the strength of inter-site relationships.

Growth-climate Relationship Analysis

This study represents a departure from previous radial growth forecasting methodology based on modeling concepts designed in the narrow scope component of this project. A more in depth description can be found in the methods section of the narrow scope paper but a general description will be given here.

A stepwise regression technique was used to establish and forecast the growth-climate relationship as it has in our previous research (Phillips and Laroque 2007, 2008). This was always accomplished by entering the radial tree growth chronologies with average monthly temperature and total monthly precipitation variables into the regression analysis. Do to the high autocorrelation of trees to previous growing seasons many growth-climate models, including those of many other studies, have always incorporated a previous growth variable in their regressions. This variable consists of the radial growth increment from the previous growing season. Although this technique has traditionally been used in dendrochronology, we felt it was potentially biasing our future forecasts. Upon its removal from the analysis, autocorrelation was accounted for by adding more climate variables from two previous growing seasons. More information regarding the specific variables used can be found in the description of monthly variables from the methods section in the narrow scope paper.

Further to the previous growth variable replacement we also instituted a new method for model selection. Previous models set aside a portion of the radial tree growth/climate variable time series. This allowed a majority of the data to be used in the stepwise regression for fitting the model and the rest of the data to be used to verify the model fit. Once all models where fitted the best verification was chosen. With a slight increase in the number of variables used in the regression it was necessary to maximize the length of the time series used in the regression to accommodate the relatively large number of variables to the relatively small number of years available. The best model is now selected using Akaike's Information Theory (AIC) corrected for models with high variable to n value ratios (Burnham 2002). Due to factors explained in the narrow scope paper, data beyond 1930 is sometimes available for verification but is not relied upon for model selection.

Geographically Focused Analysis

To locate tree ring series of the previously mentioned lengths, the geographic location in relation to climate station was not always ideal. However, due to alternate climate station data made available by the narrow scope component of this project, we were able to match the closest proximity climate station to each tree-ring sampling site for the best results.

Results

Tree Species Forecasts

Results for the modeled growth climate relationships and future growth forecasts are described below species by species.

Yellow Birch (Betula *alleghaniensis)*

Three sites were separately modeled for this species using two climate data sets. Two sites were sampled near Alma, one inside Fundy National Park and the other just northeast of the park. The two latter sites are only 17km apart and showed strong similarity to one another (Table 4).

Gagetown SF

The Slipp Farm yellow birch site was analyzed using the Gagetown climate data which extends from 1928-2002. The selected model output explained 47% of radial tree growth using 11 variables (Table 2). The model showed a very strong positive relationship to snow depth from all years, as well as a heavy reliance on summer precipitation (Table 3). This model also showed an affinity toward warm, wet previous springs and cool current Octobers (Table 3). The 21st century forecast shows little overall change in average radial growth rates in either the SRES B1 or SRES A1b scenarios (Figs. 2,3).

Table 2. Adjusted R2 values and number of variables included in the model for the AICc selected models.

Station Location	Yellow Birch		Jack Pine		Largetooth Aspen	
	Adjusted R2	# Variables	Adjusted R2	# Variables	Adjusted R2	# Variables
Sussex PV			0.535	13		
Sussex RE			0.453	10		
Sussex NB					0.373	11
Gagetown	0.473	11			0.409	12
Alma FP	0.576	7				
Alma KH	0.592	8				

Table 3. Variables chosen by AICc for each model. Prefix letter represents T for temperature or P for precipitation. Several variables represent a season (ex. Summer=Jul-Aug-Sep or J-A-S). Suffix letter represents variable year, either a=current year, b=last year, c=two years prior to ring formation.

Yellow Birch @ Gagetown SF	Yellow Birch @ Alma FP	Yellow Birch @ Alma KH	Jack Pine @ Sussex RE	Jack Pine @ Sussex PV	Largetooth Aspen @ Sussex PV	Largetooth Aspen @ Gagetown SF
+ Snow Depth a	- T Apr a	+ P Jul a	-P May b	-T Aug a	+ P Jun b	+ T Jun c
+ P Aug b	+ P Jul a	- T Jul b	+ P Jul a	-T J-A-S c	+ T Apr a	- Snow Depth a
+ Snow Depth b	+ P Aug b	+ P Aug b	- P Sep a	-T Jan c	- T J-A-S c	+ T May b
+ P Jul b	- T Jul b	- P Sep a	+T Jan b	+P Jul b	+ T Apr c	- P Jul a
+ PJul a	- P Sep a	+ T Mar b	-P Sep b	+P Jul a	- P Jun a	+ T Jun b
+ Snow Depth c	+ P Jun b	+ T Sep a	+T Feb b	-P Sep a	- P Aug a	+ T May a
+ P J-A-S c	+ T Feb b	- T Apr a	- Snow Depth a	-P May b	- T Jul b	- T Mar a
+ T May b		- T Aug a	-T May c	-P Sep b	+ T Jan c	- P Jul b
+ P May b			+P Aug B	+P Aug b	- T Feb c	- P May b
- T Oct a			+Snow Depth b	+T Jan b	+ T Jan a	+ T J-A-S c
+ T Apr c				-T Sep a	+ P J-A-S c	- P A-M-J c
				+P Jun b		- T Sep a
				-T Mar c		

Table 4. Correlation table showing Pearson correlation values between all sites of like species. See Study Sites section for expanded abbreviations.

Site	YB SF	YB FP	YB KH	Site	JP RE	JP PV	JP YC	Site	LA NB	LA PV	LA SF
YB SF	1			JP RE	1			LA NB	1		
YB FP	0.530	1		JP PV	0.546	1		LA PV	0.097	1	
YB KH	0.409	0.794	1	JP YC	0.379	0.169	1	LA SF	0.141	0.360	1

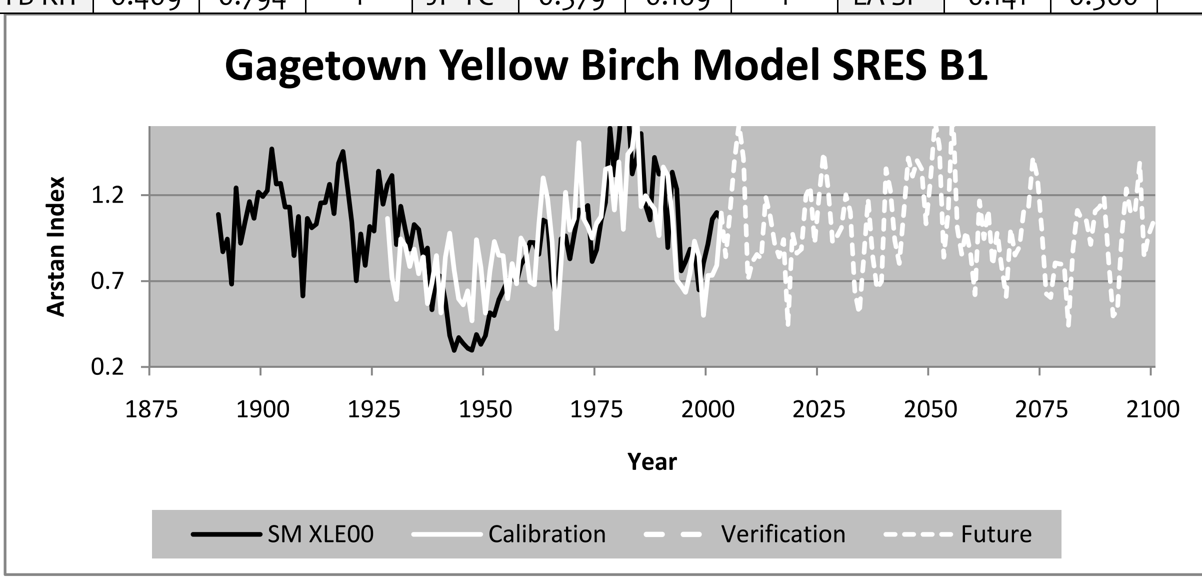

Figure 2. Modeled response of the Slipp Farm yellow birch to the SRES B1 future climate forecast at Gagetown.

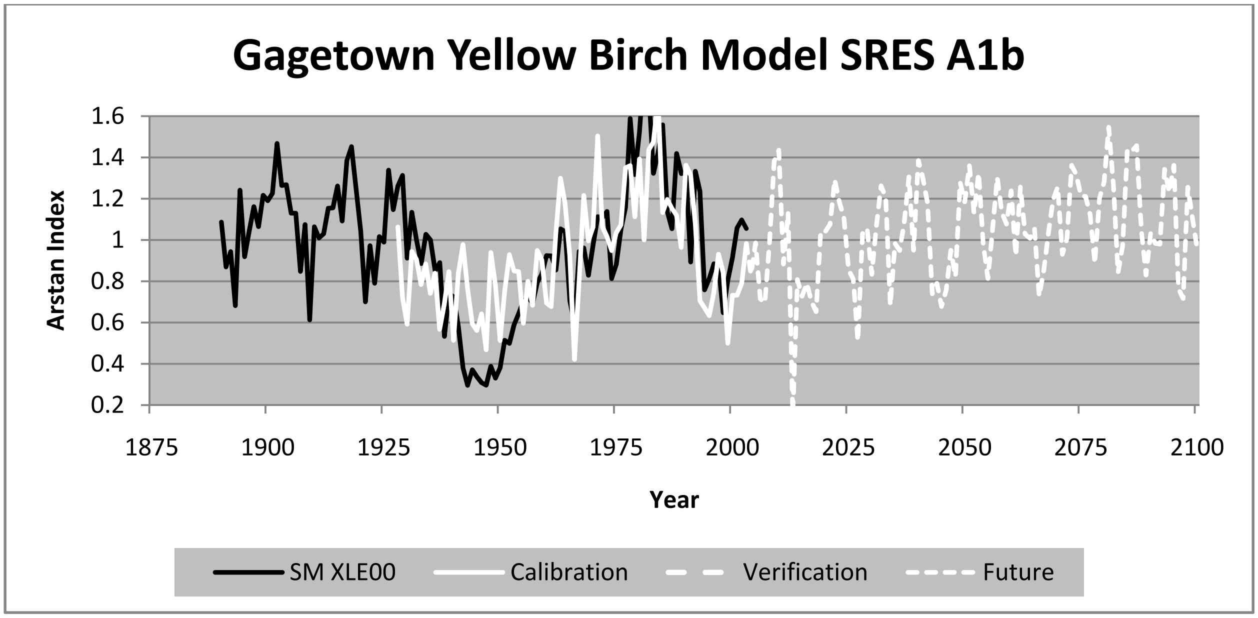

Figure 3. Modeled response of Slipp Farm yellow birch to the SRES A1b future climate forecast at Gagetown.

Alma FP

The Fundy Park yellow birch site was analyzed using the relatively short Alma climate data which extends from 1953-2002. The selected model output explained nearly 58% of radial tree growth variation using only seven variables (Table 2). Due to the short time series available here more caution then usual should be exercised when interpreting the results of this model. The model output generally reacts positively to plentiful precipitation in early to mid summer and low precipitation in current September (Table 3). Warm Februarys from the previous year are good for increased growth while cool current Aprils and previous Julys are also beneficial (Table 3). The future forecast shows an approximate 75% reduction in average radial growth rates for the SRES B1 scenario and a 100% reduction for the SRES A1b scenario (Figs. 4,5).

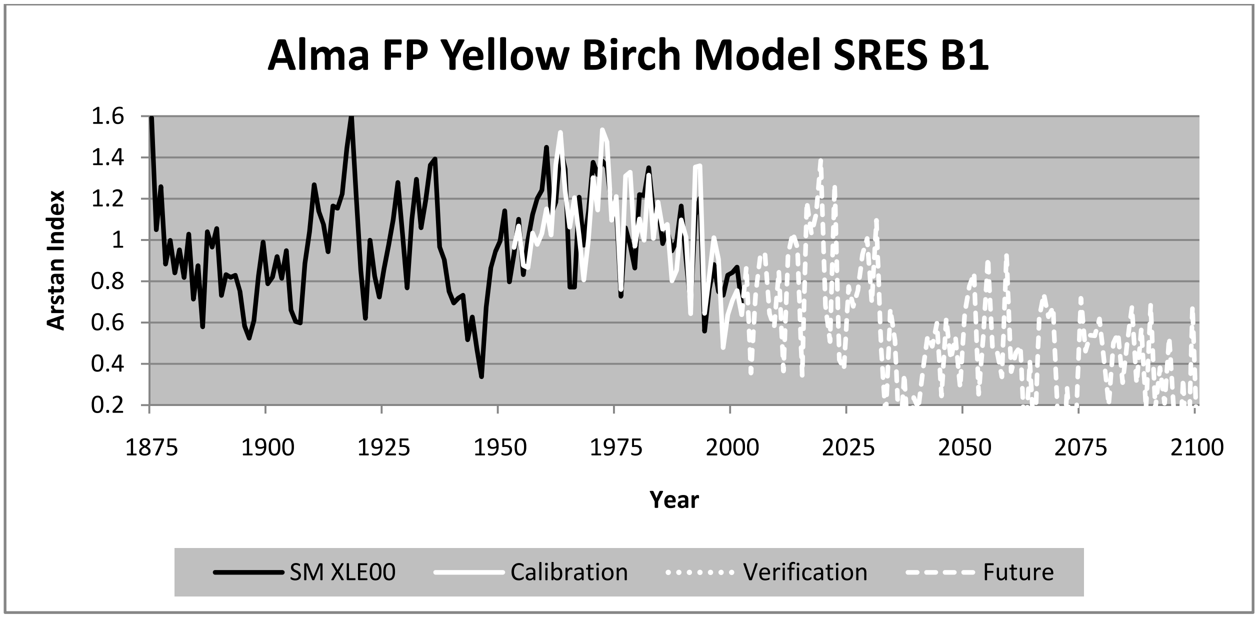

Figure 4. Modeled response of Fundy Park yellow birch to the SRES B1 future climate forecast at Alma.

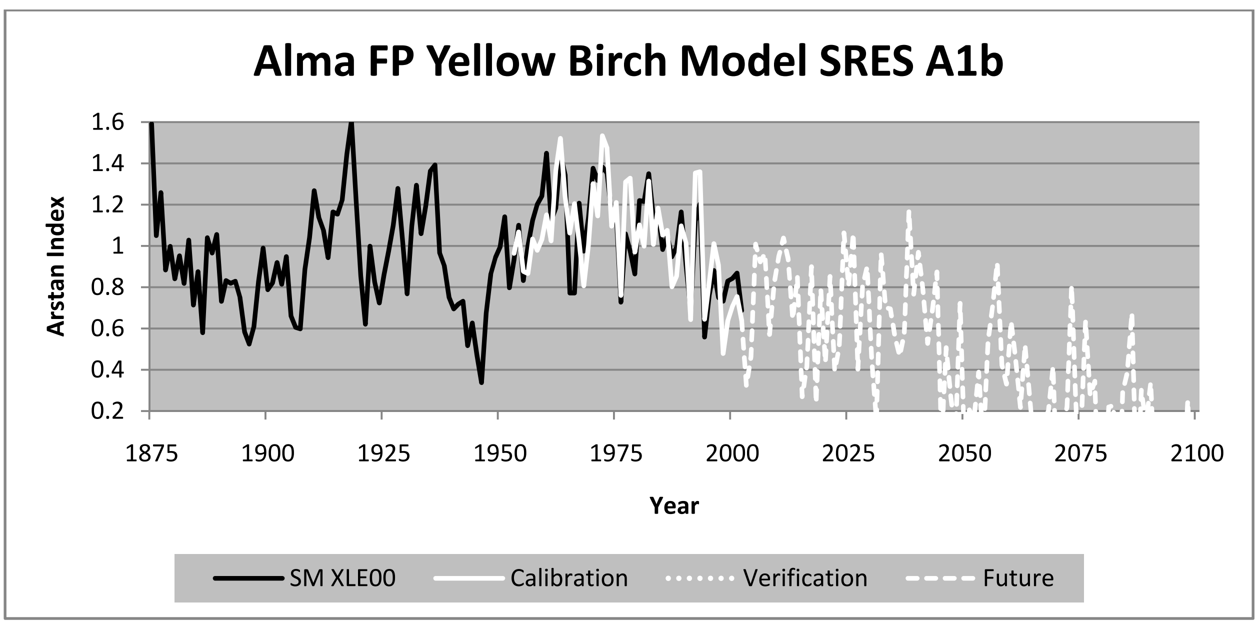

Figure 5. Modeled response of Fundy Park yellow birch to the SRES A1b future climate forecast at Alma.

Alma KH

The Kent Hills yellow birch site was also analyzed using the short Alma climate data time series. The selected model output explained 59% of radial tree growth variation using eight variables (Table 2). It is advisable to use caution with the model results due to the short time series available for analysis. This model is very similar to the Fundy Park model. The output again, generally reacts positively to plentiful summer precipitation and negatively to high current September precipitation (Table 3). In late winter and early spring warm Marchs and cool Aprils are beneficial while cool summers and warm Septembers are positive drivers of growth in the growing season (Table 3). The future forecast shows approximate 40% and 45% reductions respectively for the SRES B1 and SRES A1b model outputs (Figs. 6,7).

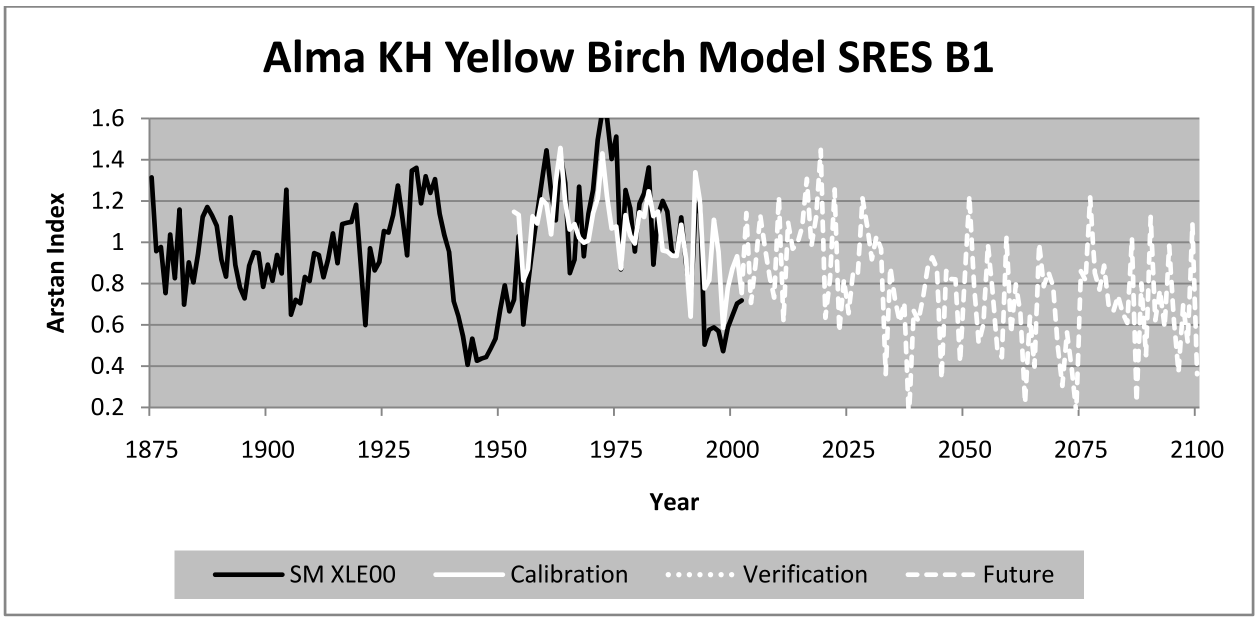

Figure 6. Modeled response of Kent Hills yellow birch to the SRES B1 future climate forecast at Alma.

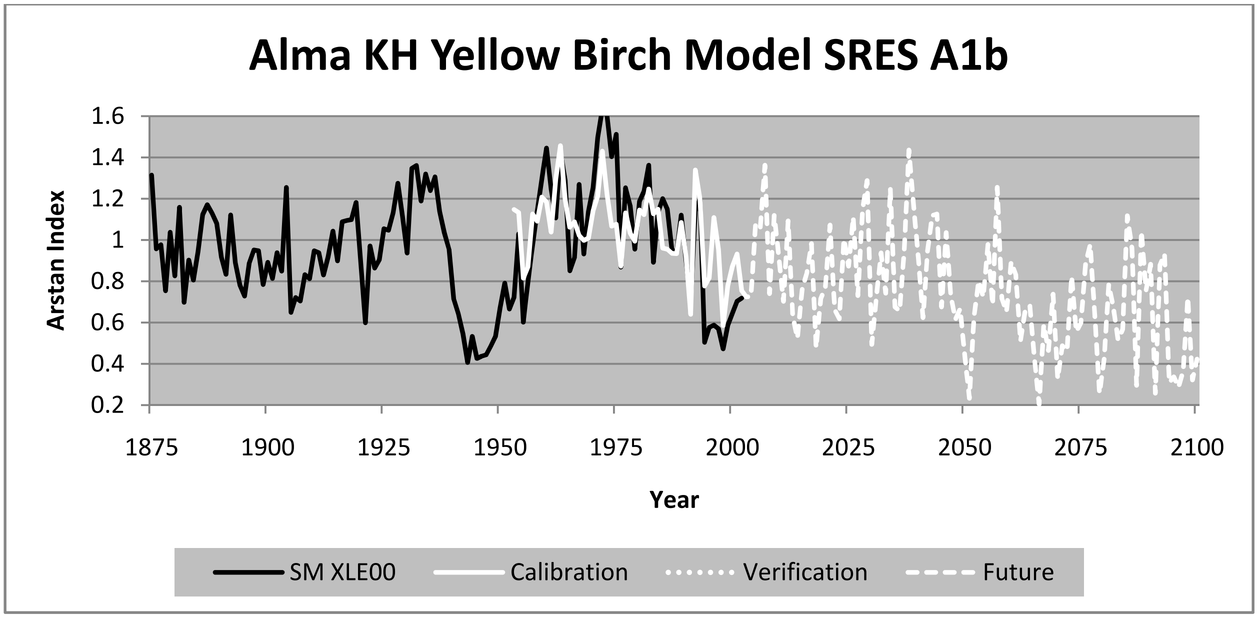

Figure 7. Modeled response of Kent Hills yellow birch to the SRES A1b future climate forecast at Alma.

Jack Pine (Pinus *banksania)*

Three sites were sampled for this species but the third site of jack pine sampled near Young's Cove presented a very weak relationship with the other two sample sites and it was eliminated from the analysis (Table 4). Models were completed for two sites near the Sussex climate data source station, Rockville Escarpment and Portage Vale.

<u>Sussex RE</u>

The Rockville Escarpment jack pine chronology was analyzed using the Sussex climate data which covers 1901-2005. As explained in the discussion section of the narrow scope component of this project, no model was run using data recorded before approximately 1930. Therefore this analysis was run using data covering 1930-2005. The selected model output explains nearly 45% of radial growth variation (Table 2). This model has a positive relationship with summer precipitation and a negative relationship with precipitation during the shoulder seasons May and September (Table 3). Cool Mays from two years prior to ring formation are beneficial and warm winter temperatures one year prior to ring formation are also beneficial (Table 3). A negative relationship with a high snow pack in the current season and a positive relationship with snow depth from the previous season complete this model (Table 3). Both SRES B1 and SRES A1b scenarios show slightly increasing radial growth rates over the 21st century (Figs. 8,9).

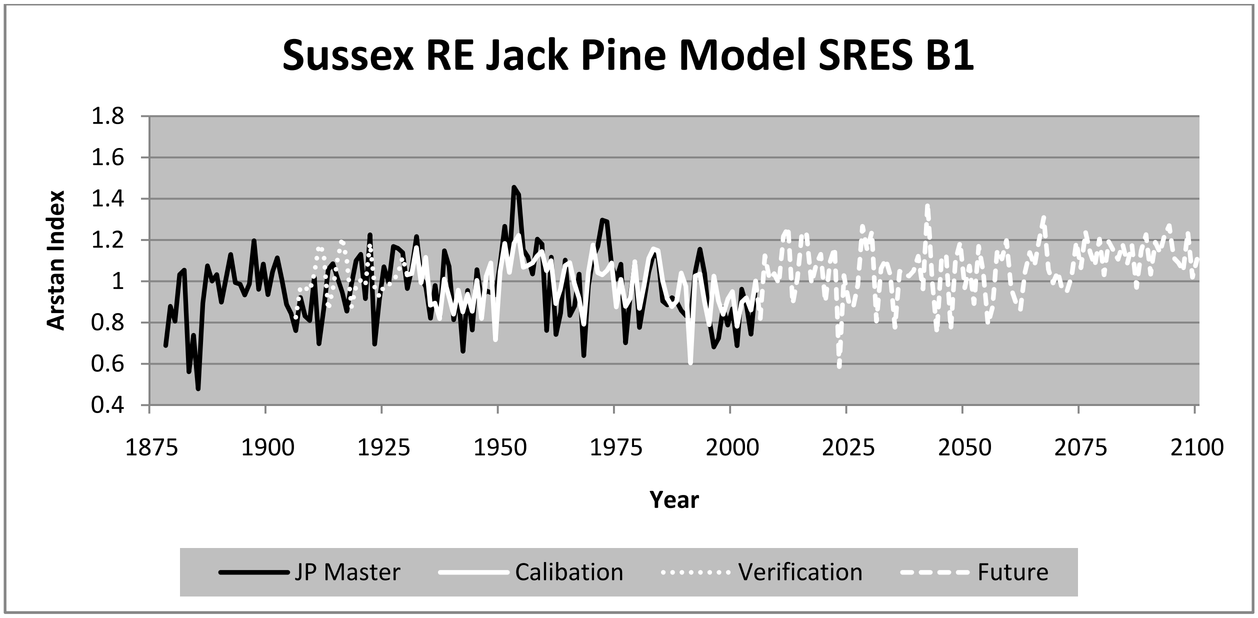

Figure 8. Modeled response of Rockville Escarpment Jack pine to the SRES B1 future climate forecast at Sussex.

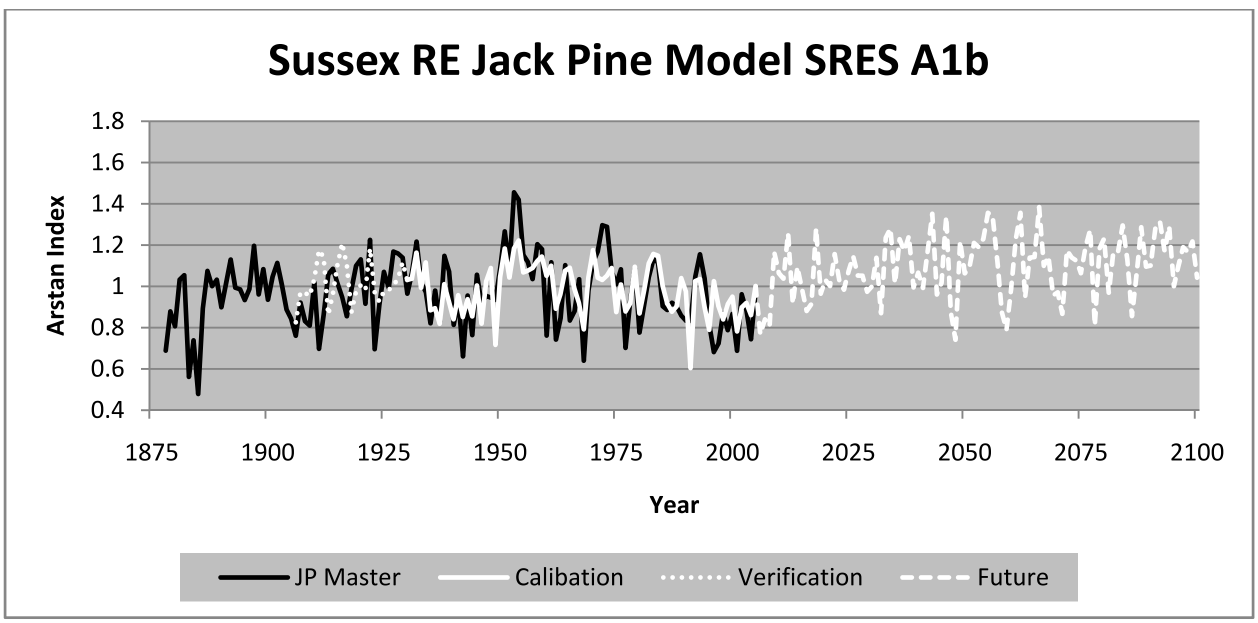

Figure 9. Modeled response of Rockville Escarpment Jack pine to the SRES A1b future climate forecast at Sussex.

Sussex PV

The Portage Vale chronology was also analyzed with the Sussex climate data 1901-2005. The model used data from 1930-2005 and the selected model output explained nearly 54% of radial growth variation (Table 2). This model showed similarities with the Rockville Escarpment jack pine model. A positive association with summer and late spring precipitation was found and a negative relation to precipitation in the shoulder seasons of May and September was again discovered (Table 3). Warm temperatures in the summer months were detrimental to radial growth as well as warm January and March temperatures from two seasons prior to ring formation (Table 3). The final variable important to this model is warm January temperatures one year prior to ring formation (Table 3). The forecasts for the SRES B1 and SRES A1b scenarios show radial growth reductions ranging from 30-40% respectively (Figs. 10,11).

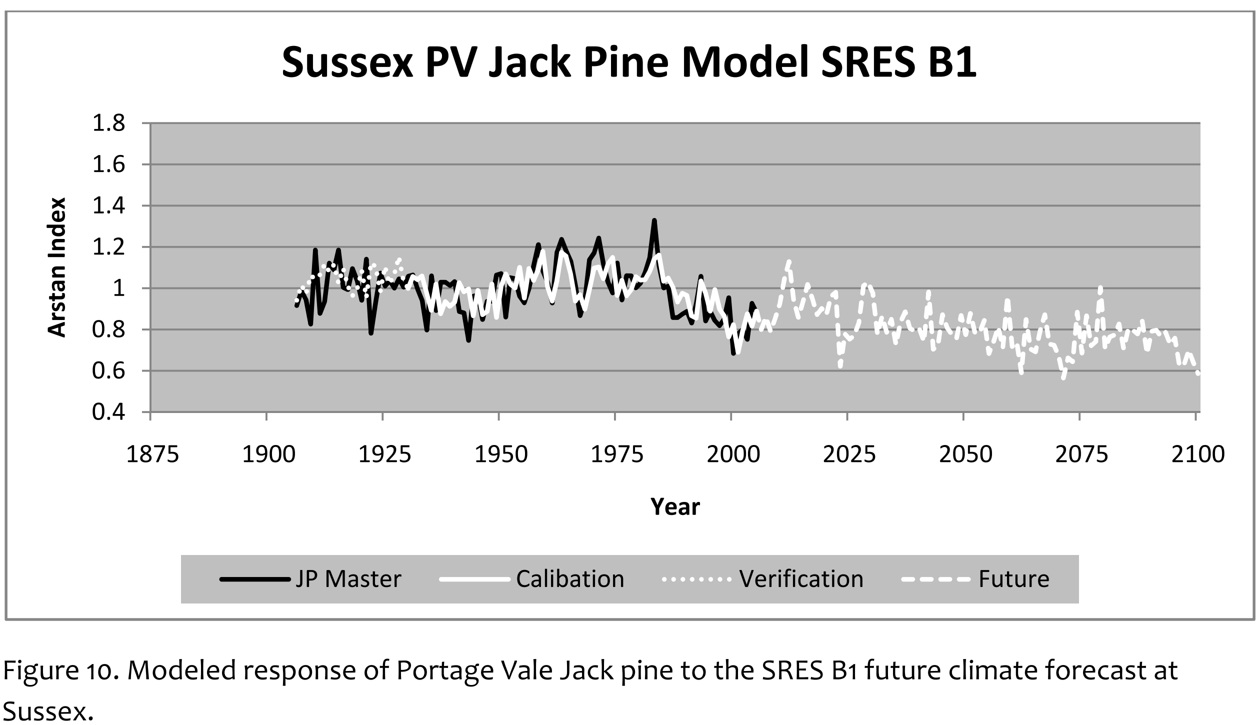

Figure 10. Modeled response of Portage Vale Jack pine to the SRES B1 future climate forecast at Sussex.

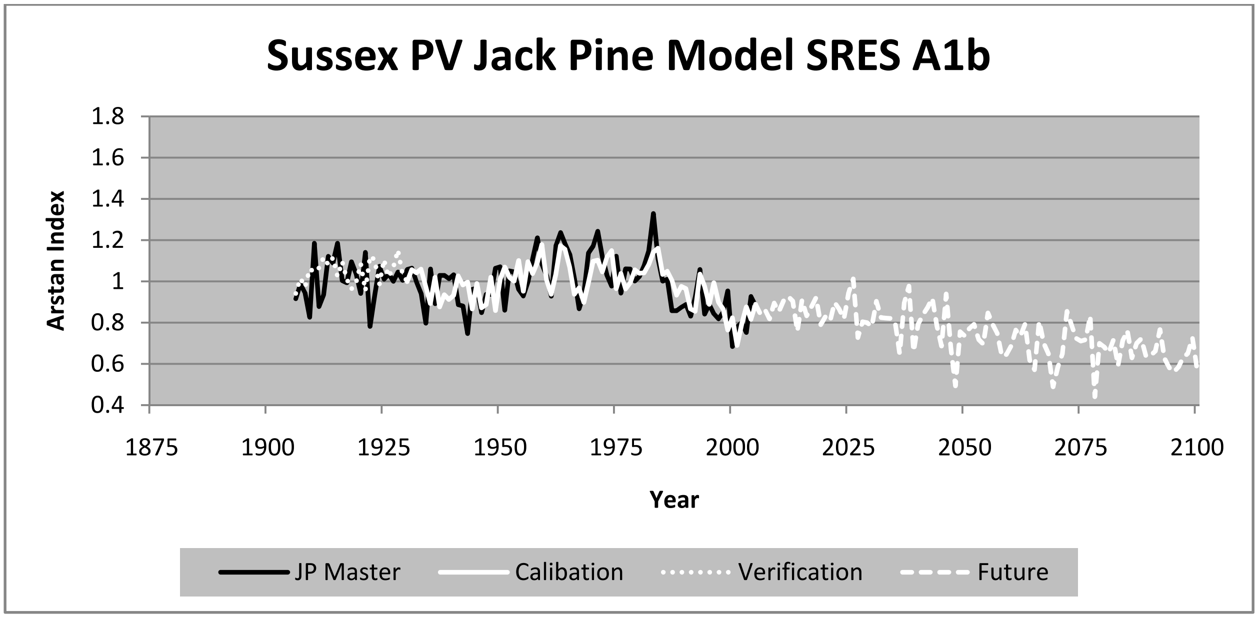

Figure 11. Modeled response of Portage Vale Jack pine to the SRES A1b future climate forecast at Sussex.

Largetooth Aspen (Populus *grandidentata)*

Three sites were sampled for this species however, one site at Portage Vale showed very poor relationships with the other two sites (Table 4). The Portage Vale largetooth aspen site was modeled but produced a very poor result suggesting this site was not climatically limited as the other two sites were. For this reason only the Slipp Farm and Negro Brook site models are shown.

Sussex NB

The Negro Brook largetooth aspen chronology was analyzed with the Sussex climate data (1901-2005). The portion of data used to produce the model ran from 1930-2005. The selected output model explained 37% of radial growth variation (Table 2). This model has a negative association with June and August precipitation of the current growing season, a positive relation to June precipitation of the prior growing season and a positive relation with summer precipitation from two seasons prior to ring formation (Table 3). Warm April and January temperatures are beneficial to radial growth while cool Julys from one season prior to ring formation and cool summers from two seasons prior to ring formation are preferred (Table 3). Lastly, cold Februarys from two seasons prior to ring formation are favorable (Table 3). The SRES B1 and SRES A1b scenarios show between 20-30% increased growth over the 21st century respectively (Figs. 12,13).

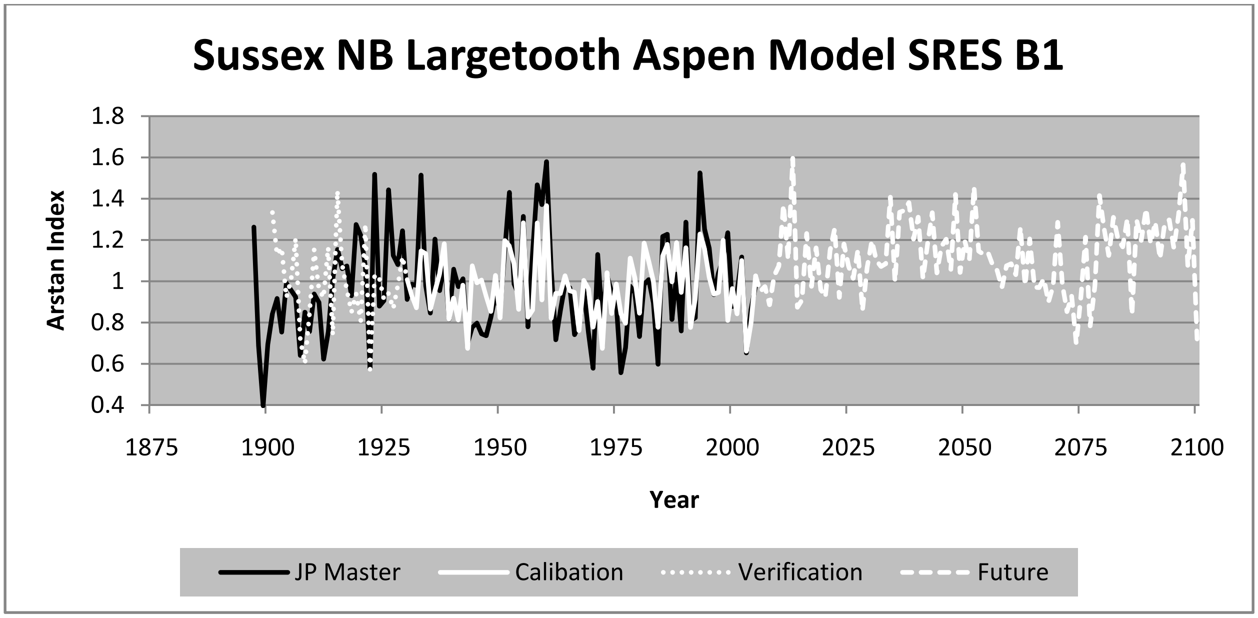

Figure 12. Modeled response of Negro Brook Largetooth Aspen to the SRES B1 future climate forecast at Sussex.

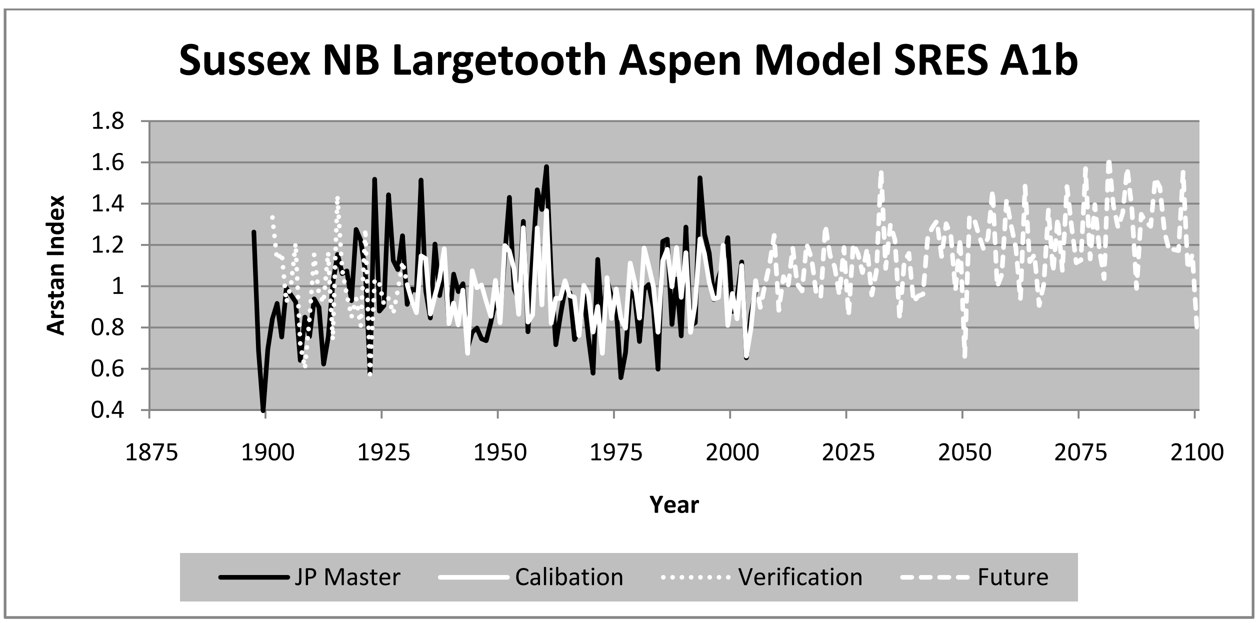

Figure 13. Modeled response of Negro Brook Largetooth Aspen to the SRES A1b future climate forecast at Sussex.

Gagetown SF

The Slipp Farm largetooth aspen chronology was analyzed using the Gagetown climate data which covers 1928-2002. The full data set was used in the analysis. The selected model output explained nearly 41% of radial growth variation (Table 2). The model was positively associated with warm mid to late spring temperature and warm summer temperatures from two seasons prior to ring formation (Table 3). Low precipitation in spring from two seasons prior to ring formation, in previous Mays and in July was related to slower growth (Table 3). Cold Marchs are preferred as are cool Septembers and low snow depth from the current season is also preferred by this model (Table 3). The SRES B1 and SRES A1b scenarios forecast a 70-90% increase in radial growth rates with this model (Figs. 14,15).

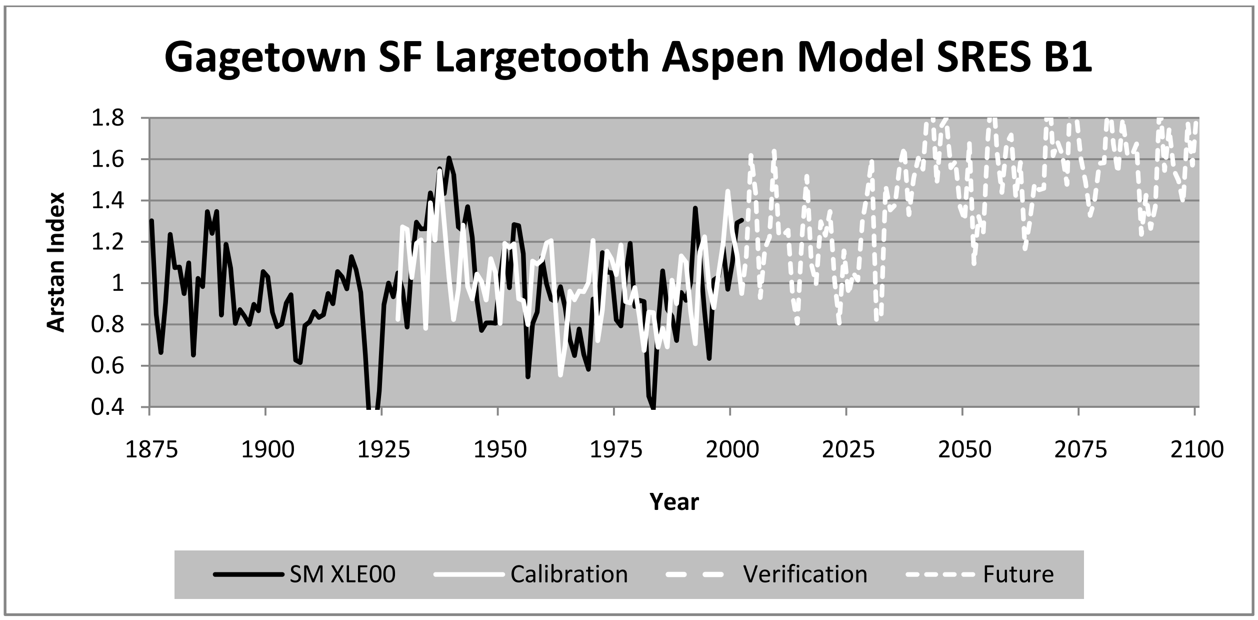

Figure 14. Modeled response of Slipp Farm Largetooth Aspen to the SRES B1 future climate forecast at Gagetown.

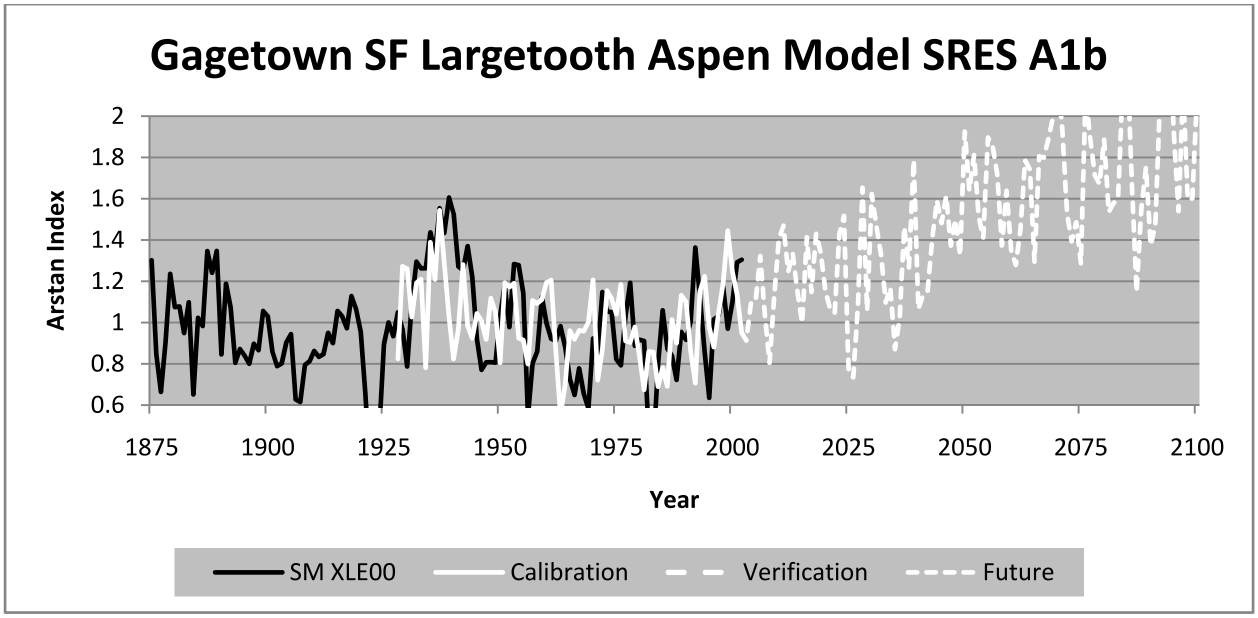

Figure 15. Modeled response of Slipp Farm Largetooth Aspen to the SRES A1b future climate forecast at Gagetown.

Discussion

Tree Growth Forecasts

The following will include individualized discussions of each forecast.

Yellow Birch (Betula *alleghaniensis)*

Gagetown SF

By considering the NBELC description of the general ecodistrict within which this sample site is located we can make sense of this radial growth model. The most important variable in this model is the positive relationship to snow depth from all years. This takes into consideration that the climate is dry and warm with evapotranspiration likely playing a large role in reducing summer water availability. A large snow pack would provide significant melt water to saturate soils before the growing season and then the second most important variable of high summer precipitation would maintain that water level throughout the warm summer. Finally warm wet springs from previous years further alleviate the water deficit. Cool Octobers of the current year's growth seem odd and maybe a spurious variable unless yellow birch is able to retain its leaves in a productive situation longer then its competitor species sugar maple and beech.

An alternate more plausible theory for the positive reaction to large snow depths is related to soil freezing and the damage of the shallow roots of yellow birch (Cox and Zhu 2003). With the removal of snow cover the roots become susceptible to refreezes and are unable to completely recover from xylem embolisms (Cox and Zhu 2003). When the snow depth variable is plotted against the past growth curve (data not shown), the long period of growth suppression beginning in the early 1930s and continuing until the early 1950s, coincides well with a long period of low snow depths. Low snow depths through the 1990s also correspond with large decreases in yellow birch radial growth rates. Although a strong relationship between yellow birch radial growth and snow depth does appear in the data, the future forecast does not show any major growth decreases. Periods of future low snow accumulation in the model may be offset by larger than normal summer and spring precipitation amounts.

This model directly addresses the water deficit which occurs more frequently at this site. The snow depth variable indirectly addresses potential freezing damage and may not be the best predictor of this type of damage. Considering future warming we would expect the yellow birch forecast for this area to be potentially more negative then is shown in these models (Figs. 2,3).

Alma FP

The NBELC description for this site shows that it is in the cool moist climate of the Caledonia Ecodistrict at a high elevation with some influence from the Bay of Fundy. The most striking aspect of this model is its high reliance on cool April temperatures. When April temperatures are plotted against the growth curve (data not shown) there is a near perfect inverse relationship. In contrast to the Gagetown forecast, we do not witness a reliance on snow depth in this model but a heavy dependence on cool Aprils which would act to keep the snow cover later into the season. Considering the climate record was recorded at a much lower elevation in Alma and that there is a steep temperature gradient between the Bay of Fundy and the Caledonia plateau, it is quite probable that the snow depth index does not fit the sample site well. So, this model is likely using April temperatures as a variable indicating when soil freezing damage is most probable. This situation is somewhat problematic as the radial growth forecast shows very substantial declines in both SRES B1 and SRES A1b scenarios (Figs.4,5). Although the April temperatures are predicted to warm substantially it is unlikely that every warm April will result in soil freezing.

Regarding the other variables in this model the positive reaction to late spring and summer precipitation are expected, as well as the negative relationship to hot Julys. The negative reaction to the current season's September precipitation is unexpected but may have to do with cloud cover and a shortening of the growing season due to a loss of warm day times and higher light levels. Finally the positive relationship to February temperatures is puzzling but could be related to heavier snow accumulation with warmer maritime air masses passing over and depositing large amounts of snow on the Caledonia plateau in that month. Although the variables in this model are sensible, particularly when comparing to the Gagetown model, it must be kept in mind the short time series (1953-2002) available to the regression analysis. The time series wasn't long enough to include the growth suppression period of 1930-1950 and so it may be leaving out important variables. Recognizing the potential for omitted variables, insignificant variables and that not all future Aprils will result in soil freezing this forecast is likely overly negative in its prediction.

Alma KH

The NBELC shows that this site is also located within the cool moist climate of the Caledonia Ecodistrict, however it is farther inland than the Fundy Park yellow birch site and should have less influence from the Bay of Fundy. This model output is very similar to the Fundy Park model but the most prominent variable, cool April temperature, although still present, is much less relied upon (data not shown). The geographical positioning of this site is farther inland and at higher elevation so it should receive increased snow fall amounts due to more orthographic lifting of winter air masses and experience colder winter temperatures than the Fundy Park site. The near sea level Alma climate data set would not represent these conditions well. Like the Fundy Park site, this model seems to use the April temperature as a variable to explain soil freeze damage which is in contrast to the use of snow depth in the Gagetown model. The forecasts produced by this model in Figures 6, 7 show 40-45% decrease in radial growth rates, driven downward by the April temperature variable. This situation is in our opinion much more realistic than either the Fundy Park or Gagetown projections as the April temperature variable does not show a near perfect inverse relationship (data not shown) to radial growth rates.

Further to the April temperature variable this model chooses a positive March temperature variable compared to the Fundy Park model's use of positive February temperatures. It is likely the two variables explain similar phenomenon. High summer temperatures and low precipitation amounts are prominent variables in this model. Again, with the geographical positioning farther away from the Bay of Fundy more summer time evapotranspiration stress would be likely. The previous June precipitation variable is gone in this model likely due to the drainage of the site. Finally, like the Fundy Park model, this model also has a September precipitation variable but this time a September temperature variable is also included. Similar caution needs to be taken regarding the short time series used in this model as in the Fundy Park model. Omitted or insignificant variables could be a problem here, particularly regarding the 1930-1950 period not modeled.

Based on the predicted future conditions of lower snow depths and more frequent refreeze events in spring (data not shown), it is likely all sites will incur damage and suffer decrease radial growth rates. Of these three yellow birch radial growth forecasts, the Kent Hills is probably the most accurate. That being said, reducing the error in the models by finding sampling sites experiencing similar conditions to the climate stations and producing more specific variables to explain tree damage events will increase forecasting accuracy.

Jack Pine (Pinus *banksania)*

Sussex RE

This site's geographic position in the Anagance ecodistrict is described as warm and dry by the NBELC. It is on the leeward side of the Caledonia plateau receiving less precipitation than the windward side, it is on a well drained slope and it has a southwest facing aspect ensuring maximum sunlight exposure. As would be expected this model relies upon adequate summer precipitation to produce radial growth. A negative association with shoulder season precipitation in the form of May and September variables exists which may have to do with lower evapotranspiration rates during periods of shorter sunlight hours. Less cloud cover in these months would boost the amount of photosynthesis possible during the growing season. Cool May temperatures from two years prior to ring formation benefit radial growth, possibly related to evapotranspiration since few deciduous trees are present on this site to leaf out and create competition during May. Conflicting snow depth variables from the previous season and the current season are confusing and mainly serve to cancel each other out. The overall driving force behind the slightly increased growth in the forecasts for this site is the positive association with winter temperature variables. Both January and February of the previous season are beneficial to growth in the model and both are expected to increase over time. The biological significance of warm mid-winter temperatures for jack pine trees is not obvious however.

Sussex PV

The positioning of this site is very similar to the Rockville Escarpment site in terms of ecodistrict, rain shadow, slope drainage and aspect. The main difference between sites is competition difference due to the mix of aspen and jack pine at the Portage Vale site compared to the dominance of pines at the Rockville site. The Portage site shares the same variables regarding summer and shoulder season precipitation and has two extra summer precipitation variables. The forecasts for this site show substantial future radial growth decreases under both climate change scenarios modeled (Figs. 10,11). The Rockville site showed increasing future radial growth due to increasing winter temperatures and this site also uses a positive January temperature variable. However, two winter variables of January and March from two years prior to ring formation show a negative association with radial growth. The projected warming trend of these winter months partially contributes to the forecasted radial growth decreases modeled here. Other factors contributing to decreases include a negative relationship to summer temperature variables, which are projected to increase over the 21st century. Also a negative association to warm September temperatures is partially responsible for driving future radial growth rates lower as September temperature is also expected to warm. This final September temperature variable is counterintuitive but is likely related to the early leaf drop of the associated aspen portion of the tree stand.

Both the Rockville Escarpment and Portage Vale models contained conflicting variables regarding winter temperatures and snow depths making their future influence on radial growth questionable. Considering the warmest winter temperatures of the entire jack pine range are experienced in the Maritimes it is sensible that warmer winters may be detrimental to the species (Burns et. al 1990). If warmer winters are to affect the radial growth of jack pine they will have to warm substantially as past warm winters have not caused major problems for the trees. The most probable cause of future radial growth reductions will be summer precipitation rates. If droughts are more common jack pine may suffer some radial growth rate decline but other areas of its range receive far less precipitation then the trees will ever experience here in the near future. Given the output of these models and the future climatic changes anticipated jack pine should at most, only experience small decreases in radial growth rates.

*Largetooth Aspen (*Populus *grandidentata)*

<u>Sussex NB</u>

This site is similar to the other Sussex sample sites except that it is more flat. The slope faces southwest and the climate is dry and warm. This model shows substantial increases in forecasted radial growth rates which can be attributed to the models reliance on the April temperature variable from the current season and two seasons prior to ring formation. Predicted warmer Aprils and a positive association with January temperatures from the same seasons drive the model upward. Negative growth responses driving the model downward include both the previous July temperature variable and the summer temperature variable from two seasons prior to ring formation. The positive and negative associations to various precipitation variables would do little to change the direction of the modeled radial growth. The unknown factor in this model is the past effect of the forest tent caterpillar (Malacosoma *disstria).* Largetooth aspen is known to be periodically defoliated by the forest tent caterpillar for several consecutive years (Laidly 2004). A biotic effect such as the tent caterpillar could cause spurious variables to occur in the model or cause important variables to be left out.

<u>Gagetown SF</u>

This site is located in the warmest part of the province with a dry climate. The stand of largetooth aspen faces the west at the top of a steep rocky slope. This model forecasts very large increases in radial growth rates for largetooth aspen. The main driver of the increasing future growth rate is positive association to warmer mid to late spring temperature variables and temperature variables from summers two seasons prior to ring formation. Many variables associated with spring and summer precipitation are an important part of the model but do not appear to drive the forecasted growth up or down. The snow depth variable in the model contributes to the increasing future growth rates but it is unknown why lower snow depths are preferred by this species.

Both the Negro Brook and Slipp Farm largetooth aspen models show a negative relationship with high amounts of precipitation in key parts of the growing season when water may be important. Due to the high shade intolerance of this species it appears that it is willing to go without water from precipitation in order to have clear skies and increased photosynthetic potential. Warm springs are preferred as evidenced by several other temperature variables leading to the hypothesis that long growing seasons with moderate temperatures and maximum sunlight hours will produce the greatest radial growth rates. Warmer springs will become the norm, extending the growing season as the climate warms. This should certainly increase future growth rates of this species but it remains questionable as to how much growth rates will increase. The modeled forecast for the Negro Brook sample site seems easily achievable by centuries end under the climate change scenarios provided. The Slipp Farm modeled forecast should be scrutinized as the trees in the sampled stand are very old and have grown incredibly slowly for the largetooth aspen species. It should also be kept in mind that the Portage Vale largetooth aspen chronology did not correlate with the other two sites and that other growth/climate relationships may exist for this species.

Model Limitations

The accuracy of the forecast models created in this study are limited by the predictive accuracy of the CGCM3 data. Global Climate Model data is an evolution in progress, constantly being updated, redefined, and ceaselessly being fed better and more spatially continuous data. As such, the future predictions of this study need to be qualified by the ability of the modeled data to forecast scenarios set forth by the IPCC. As future scenarios change, and new generations of models are produced, the forecasts derived for future radial growth will also need to be updated. It is doubtful our climate change trajectory will ever be steady or assume a constant level. We are currently on an accelerating climate change direction above all current IPCC SRES scenarios (Raupach et. al 2007). If this trajectory continues the forecasts produced in this paper may happen in a fraction of the century long time frame specified in the climate change scenarios used.

Another limitation of the forecast models is the availability of past climatic situations that are analogous to future climatic scenarios. The forecast models in this study are based on the past approximately 75 years of radial tree growth in comparison to the past 75 years of historical weather data. During this 75 year period there has been much climatic variability but there are potentially future forecasted climatic maximums of both temperature and precipitation that are outside of the range of the past climates. A prime example of this would be future winter precipitation falling as rain instead of snow, drastically changing factors relating to growth (Laroque and Smith 2003, Goldblum and Rigg 2005). The models are therefore, somewhat limited in their capacity to provide a completely accurate prediction of radial growth under the forecasted climatic range that is outside of that experienced in the past. Ecological thresholds that relate to a tree's response to temperature or precipitation of a particular month or season may not have been reached in situations in the past 75 years and could therefore be missing from the forecast models. Consequently, as the models work their way into more extreme climate change scenarios it is expected that their predictive capability will begin to fail which is why more extreme SRES scenarios are not modeled here.

The potential for a particular species to modify specific climatic factors that it is dependent upon as it reaches possible climatic thresholds remains unknown. We do know that climate-growth relationships are not age independent (Carrer and Urbinati 2004). The degree to which physiological changes in the studied tree species have altered their response to climate inputs over the timeframe investigated is obscured by our process. How much future physiological changes will impact the radial growth response to future climates is also not known and could play a large role in keeping a particular species competitive or contributing to its demise.

It should also be kept in mind that these models are only predicting radial growth response to the future climatic inputs and do not at all account for radial growth reductions inflicted by insect outbreaks or other pathogens. As the climate warms trees will not be the only species to shift ranges in response to the new conditions. Other species will also have a migrational response that could differ substantially in geographical and temporal scales. Therefore, it should be anticipated that future radial growth of trees could be significantly affected by influences other then the changes of temperature and precipitation brought about by climate changes. This fact and the fact that the trees currently rooted in place versus the ability of insects to more readily disperse cannot be taken into account in our models.

Although there are many potential external and internal sources of error in these biologically based, deterministic models, we believe that they present the most accurate picture of future radial growth rates to date in the AFR. Most importantly, anthropogenic response to a warming globe represents the largest source of error and cannot be corrected for until tomorrow's future becomes today's reality.

Conclusion

Radial growth forecasting shows much promise as a forest management tool in the face of a changing climate. Methodological obstacles can hinder the certainty of forecasts produced and this paper puts to practice some of the lessons learned in the narrow scope component of this project. Through the use of more site specific climate data, by adopting new model selection techniques and by adapting the climatic variable set used in the stepwise regression model, the model outputs produced are heading in the direction of greater certainty. The forecasts produce here show decreased future radial growth rates for yellow birch, possible small decreased radial growth rates for jack pine and increasing radial growth rates for largetooth aspen. Depending on reaction to climate change by the global community these forecasts are likely to take affect earlier rather than later.

Although improvements in the radial growth forecasting technique have manifest themselves in more detailed and descriptive forecasts, limitations are still evident. Future implementation of radial growth forecasting should focus on tightening the gaps between sample site and climate station discrepancy and work on defining variables that best describe the tree specie's biological perception of climate.

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