MAD LAB

Mount Allison Dendrochronology Lab

Future Radial Growth Forecast for Six Coniferous Species In Southeastern New Brunswick

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Abstract

Many people depend on forests to provide a wide range of necessities while believing forests are a static, non-mobile community. Future climates are now challenging that traditional perspective and are forcing us to reconsider our reliance on forested landscapes. The goal of this study is to project the radial growth of the most regionally important coniferous tree species over the 21st century in an attempt to mitigate economic and conservation problems before they occur. In this study, six species of coniferous trees from Southeastern New Brunswick are investigated to produce future radial growth predictions for presently standing trees and their progeny.

Examining the past relationships of the tree species and historical climates was achieved through regression analysis between archived weather data and past radial growth data sampled from living trees. The species specific relationships are then forecast over the period 2000 –2100 A.D. using multiple scenarios of coupled general circulation model outputs. Results indicate a range of responses that indicate some species will flourish while others will decline. Eastern hemlock will benefit the most from the forecasted future climates taking full advantage of a longer growing season while Eastern white cedar will fail to produce the necessary radial growth to maintain a competitive edge. White pine is forecasted to continue to grow at historical rates, while three species susceptible to insect infestations (black spruce, red spruce and Balsam fir) are projected to continue to exhibit stable growth patterns (Balsam fir) or have enhanced growth (black but especially red spruce) under future predicted climates.

1.0 Introduction

Climate change will and has always affected the growth and integrity of forests across the globe. Recently, attempts have been made in eastern North America to forecast future species composition and radial growth changes in response to the changing climates. In New England, certain forest communities, mainly spruce-fir and aspen-birch, have been predicted to be extirpated from the American landscape (Iverson & Prasad 2001). In Canada the Canadian Forest Service (CFS) has developed models showing tree species range changes that should result from the trees following future relocation of climate zones (McKenney et al. 2006). The studies show a general northerly migration of tree species and vastly different forest communities left in the wake of this migration.

In the Maritimes during the last interglacial interval known as the Sangamon period, evidence suggests the forest community was composed of more temperate species which currently inhabit areas to the south of New Brunswick, but which require a much warmer climate to grow (Mott 1990). Following the Wisconsin glaciation, the Maritime vegetation quickly transitioned from tundra/arctic pioneer species through successional boreal tree species to a climax of temperate species, mainly white pine, hemlock and oak (Ritchie 1987; Jetté & Mott 1995). This climax was reached during the Hypsithermal interval, which occurred between 5,000 and 7,000 years ago. After this peak the regional climate slowly cooled by about 2°C forcing the forest to adapt by reverting to a more boreal component of spruce and fir (Delcourt & Delcourt 1987). Currently the forest covering the three Maritime Provinces is maintained by a transition zone climate which separates the conifer-dominated boreal forest to the north and the mainly deciduous temperate forest to the south. With climate now changing in an unprecedented fashion, the development of a regional, comprehensive forecast that outlines imminent changes to radial growth patterns is crucial to forest managers.

The forest landscape has been changing towards a more boreal type ecosystem as historical and industrialized forestry practices continue to selectively alter species distributions through various means. It has been proposed that a warming climate will force the naturally occurring forest composition to convert back to a more temperate, deciduous condition. The two fast paced anthropogenic forces of climate forcing and logging are influencing species distribution in opposite directions. Both of these factors have the independent potentials to cause dangerous economic and ecological shifts in forest health. Due to the longevity of logging and the swift action of climate change the sustainability of Maritime forests could be at risk. The reaction of specific tree species to potential climate changes needs to be answered to avoid future catastrophic economic and ecological losses. Therefore, the development of radial growth forecasts is a crucial first step and this study starts that process.

2.0 Background

This analysis was designed to assess a manageable number of the most economically and ecologically important coniferous tree species in the Fundy Model Forest (FMF) region, so as to provide relatively quick and important results on the past and potential future radial growth trends of our current forests. Since the most relevant species were required for the study (regarding economic and ecological importance), input was sought from stakeholders to help determine which species should be used. The Southern New Brunswick (SNB) Woodlot Co-op and Parks Canada were approached as the major stakeholders located within the study area who could provide meaningful feedback with species preference.

2.1 Resource enhancement

Forestry is a very important industry in the Maritime Provinces to both industrial logging companies and local small woodlot owners. The future supply of available timber is paramount to a successful and profitable industry. Currently most forest industry sectors rely on traditional growth and yield models that are based on linear projections. These projections assume past radial growth is a dependable indicator of future forest productivity. Combined with this productivity assumption is the widely accepted idea that forest composition will remain in a stable state for perpetuity.

Previous studies conducted by the Mount Allison Dendrochronology (MAD) Laboratory have shown that all coniferous species in the Maritime Provinces produce annual radial growth rings with substantial year to year variability (Laroque 2005). Climatic conditions play the largest consistent role in this radial growth variability which means any changes in long-term climates should affect annual allowable cuts (AAC) substantially. If the forestry industry does not anticipate these changes, positive or negative, a great deal of economic opportunity could be lost. The prospect of knowing which tree species may grow better in the future would be very advantageous leading to, for example, an improved understanding of which stock to replant for maximal benefit. It is one of the goals of this study to begin the introduction of a variable model based on the best future climate predictions available. The estimates provided through AAC need to be corrected for climate variation and long term changes in order for the industry to maintain its profitability.

2.2 Conservation success

As temperatures increase in New Brunswick some tree species will become winners and some will become losers. Changes in tree species distributions and concentrations will lead to many ecosystem transformations. All other species living in forests, whether small plants or large animals, stand to be affected. Unanticipated tree species range migrations will create great difficulty for conservationists. Conserving an ecosystem that cannot continue to exist under changing conditions could be a futile effort. Protected area locations could be severely undermined and reforestation goals could be unproductive. The resulting forecast from this project is aiming to help forest managers working in conservation areas to anticipate and plan for future predicted forest reactions to a warming globe. By attempting to develop a future forecast this study hopes to deliver the knowledge to better use future resources in conservation efforts. In both cases those who work in the forest will gain the ability to plan ahead of climate change instead of reacting to it.

3.0 Main Objective

The main objective of this study is to collect representative growth data from five important species in the FMF region and based on past growth and climate relationships, forecast radial growth pattern in the region for the next 100 years.

4.0 Study Site

4.1 Site description

The centrally located area of southeastern New Brunswick was chosen as a representative ecosystem within the Maritime region of eastern Canada for collection of past radial tree growth records and past weather data. Southeastern New Brunswick is located between 45° and 46°50′ north latitude and 63°50′ and 66° west longitude and the elevation ranges from sea level to a maximum of 400m asl. This area is covered by four of the seven distinct New Brunswick eco-regions as defined by the Ecological Land Classification, giving it a strong representation of tree species diversity occurring throughout the Maritimes region (Power & Matson 1995). The combination of lowlands, uplands, coast, and valley landforms has resulted in the four eco-region classifications. The climate varies over this region as the influence of coastal waters, elevation, and inland air masses contribute to 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 400-500mm (Clayden 2000). Although this variability exists there is still a strong similarity between all four eco-regions as the latitudinal difference and elevation changes are not significant enough to bring about large climatic divergence.

4.2 Tree-ring sampling

Increment cores were collected from trees at 17 sites scattered over southeastern New Brunswick (Fig. 1). Twenty trees were selected at each site, and cored twice for a total of 40 cores per site. Of the five species identified by the stakeholders, one was thought to be too short lived to locate enough old trees required to meet statistical reliability for the project. Originally red spruce (*Picea rubens*), black spruce (*Picea mariana*), white pine (*Pinus strobus*), eastern white cedar (*Thuja occidentalis*) and balsam fir (*Abies balsamia*) were selected.

Balsam fir was replaced by eastern hemlock (*Tsuga canadensis*) due to the anticipated problems of locating sufficient and old enough trees. Each species was sampled at three locations within the study area. One site of acceptably old balsam fir was found within the boundaries of Fundy National Park which happened to be key to Parks Canada, the stakeholder group interested in balsam fir, and so a sixth species was attempted in the study, but based solely on the one site.

Importance was given to finding sites that were geographically separated by at least 30 km within the study area, however, to locate stands of acceptably old trees this was not always possible. At least 100 years of radial tree growth was required for the analysis which was difficult to find for some species. All sample sites contained the particular species of investigation in a mature dominant or co-dominant role except for the one site containing balsam fir. At this site, the fir was scattered as individuals among the more continuous forest. To find trees of at least 100 years of age, site differences such as slope, aspect, elevation, substrate and marine proximity had to be ignored. These site to site differences, no doubt, contributed to variance in radial growth observed upon tree ring measurement but micro-site characteristics were of no concern to this study as the general climatic conditions and their relationship to radial growth was the focus of the study.

Figure 1 – Map of Southeastern New Brunswick with locations of all tree species sample sites. The location of the three largest communities on the region are also displayed.

4.3 Climate data

Weather data used for the analysis was collected from Sussex for the period 1897-2002 (Fig. 2). Sussex is centrally located within southeastern New Brunswick, is far enough away from direct marine influences and is located within a river valley lowland area. When compared with historical weather data collected from the other largest Southeastern New Brunswick communities of Moncton and Saint John, Sussex showed nearly identical temperature and precipitation quantities through most months of the year. For this reason the Sussex data was taken to be representative of Southeastern New Brunswick.

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 used in tree growth forecasts. The 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 (Fig. 2).

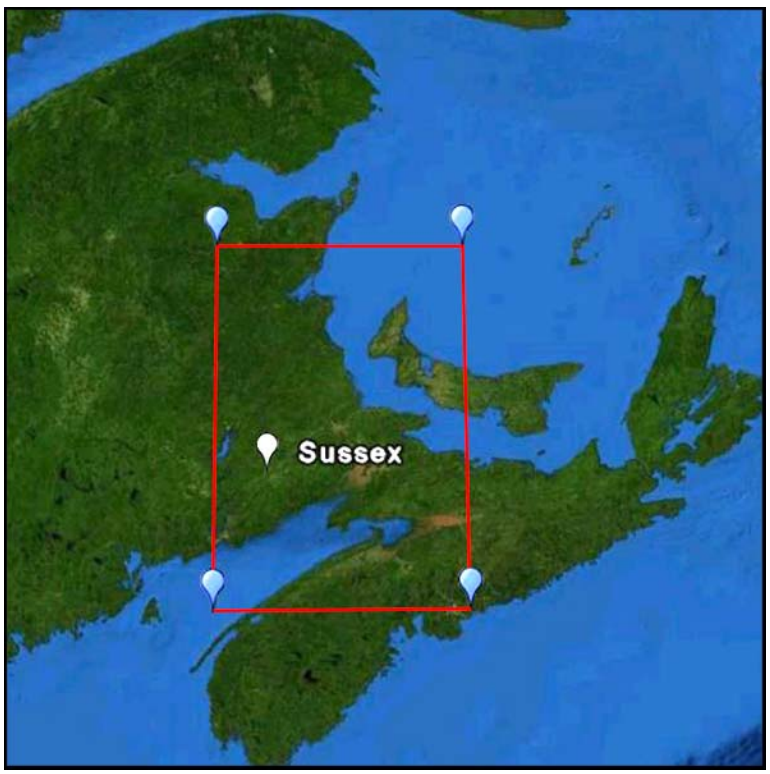

Figure 2 – CGCM3 grid square covering Southeastern New Brunswick that was used in this study.

5.0 Methodology

5.1 Future climate data calibration

The climate model grid square overlaying Sussex covers an area of 2.81˚ latitude by 2.81˚ longitude. This relatively large zone, compared to the much smaller region of Southeastern New Brunswick, incorporates many marine influences including a large portion of the Bay of Fundy, the Northumberland Strait and a section of the Gulf of St. Lawrence. The inclusion of these bodies of water influences the CGCM3 output significantly. An average result of temperature and precipitation is forced over the entire zone that does not necessarily represent all areas of the grid square to an accurate degree. The consequence of this generalization is a climate model data set which is approximately 2.5˚C cooler on an annual average than the Sussex data. The seasonal and monthly values of the CGCM3 deviate from the Sussex historic data in various ways. To correct for the problems encountered with the differences in geographical scale and season, a conversion was carried out on the climate model data. The CGCM3 data was subtracted from the Sussex historical data on a monthly scale for each year during the period 1900 – 2000. The results were averaged for each month to create a mean monthly divergence value. These average monthly values were then applied back onto the annual CGCM3 figures at the same monthly resolution. The outcome of this correction was a modeled past climate data set that matched the past Sussex data in magnitude. The same correction was then applied to the future data set which adapted the zonal CGCM3 data to the land based point source conditions experienced in Sussex.

5.2 Tree-ring data

Increment cores were measured, cross dated and individual master chronologies constructed for each site following standard dendrochronological methods. The individual masters were then entered into a 3 X 3 correlation matrix to determine how much divergence existed between sites. All sites were well above the critical correlation levels and significant to at least the 99% level. A visual examination of the degree of similarity was also conducted. Following the site to site testing, species master chronologies were constructed by averaging together the three individual site master chronologies for each species.

5.3 Past climate data

Species masters were then entered into regression models with monthly resolution climate data, including both temperature and precipitation, collected in Sussex, New Brunswick from 1900 to 2000. In the regression models, temperature and precipitation data from Sussex consisting of the first nine months of the current year and all months from the previous year were used amounting to 42 variables. An independent variable was also added for one year's previous tree growth in each species specific model. This was done due to expected high auto correlation values between the current and previous year's growth as evidenced in most dendrochronological studies (Fritts 1976). These 43 variables were examined in a forward stepwise multiple regression analysis which established the most important factors contributing to annual radial growth in a sequential order for each species. The process identified months that most significantly contributed to radial grow and these variables were then entered into an equation which calculated the past, and then were used to calculate the future annual radial growth response of trees to forecasted climates.

5.4 Model Calibration and Verification

The model of tree growth response to climate was established using a 10% rule of thumb to the identified climatic factors contributing to annual radial growth in the regression analysis. For example, this meant that since the Sussex data had approximately 100 years of instrumental data, a maximum of 10 variables could be used in a regression equation to guard against over-fitting of the data. This value actually was lower, as we limited our models to 10% of the calibration time of each modeled data set For the species of white pine, hemlock and cedar, a 60/40 calibration to verification ratio was used, meaning that a maximum of 6 variables could be used in the model. The resulting models based on past relationships, were then applied to the future corrected climate data to produce annual forecasted radial growth values.

5.5 Spruce Budworm Effected Species Models

The selected group of tree species contained three species which are susceptible to spruce budworm defoliation including red spruce, black spruce and balsam fir. The area of Southeastern New Brunswick has been significantly affected by spruce budworm three times during the past century and the spruce sawfly was also responsible for a single defoliation event in this time interval (Brown 1970; Kettela 1983; Woodley et al. 1998). Both of these insect infestations have left the effected tree species with severe radial growth declines during the defoliation periods. The result is a radial growth impact disconnected from climatic influence that cannot be modeled using only climatic variables. The solution to this problem was to use the insect induced radial growth reduction periods as the model verification periods. These periods combined for approximately 30 years of data which in the end produced a 70/30 ratio of calibration to verification for each model for the three species.

5.6 Climate Model Scenarios

The International Panel on Climate Change (IPCC) has set out various social scenarios that indicate the projected amounts of CO2 that will be in the Earth's atmosphere by the end of the 21st century in their Special Report on Emissions Standards (SRES). The CGCM3 calculates data based on these scenarios and two of them were used in this study. The first scenario used was the SRES B1 which is based on 550 ppm of atmospheric CO2 by 2100 which is a conservative estimate (Fig. 3). The corrected data from this scenario shows a temperature increase of approximately 3˚C between 2000 and 2100 for the Sussex area. Precipitation for this scenario shows significant variability but overall it only increases marginally by approximately 30mm annually by 2100.

The second scenario used was the SRES A1B which is based on 720 ppm of atmospheric CO2 by 2100 which is the upper level estimate (Fig. 4). The corrected data from this scenario shows a temperature increase of approximately 4.5˚C between 2000 and 2100. Precipitation for the 720 ppm scenario also shows significant variability but this time the mean trend of the data increases more rapidly by 100 mm in the first 80 years of the 21st century until it quickly declines back to 2000 levels at the 2100 mark.

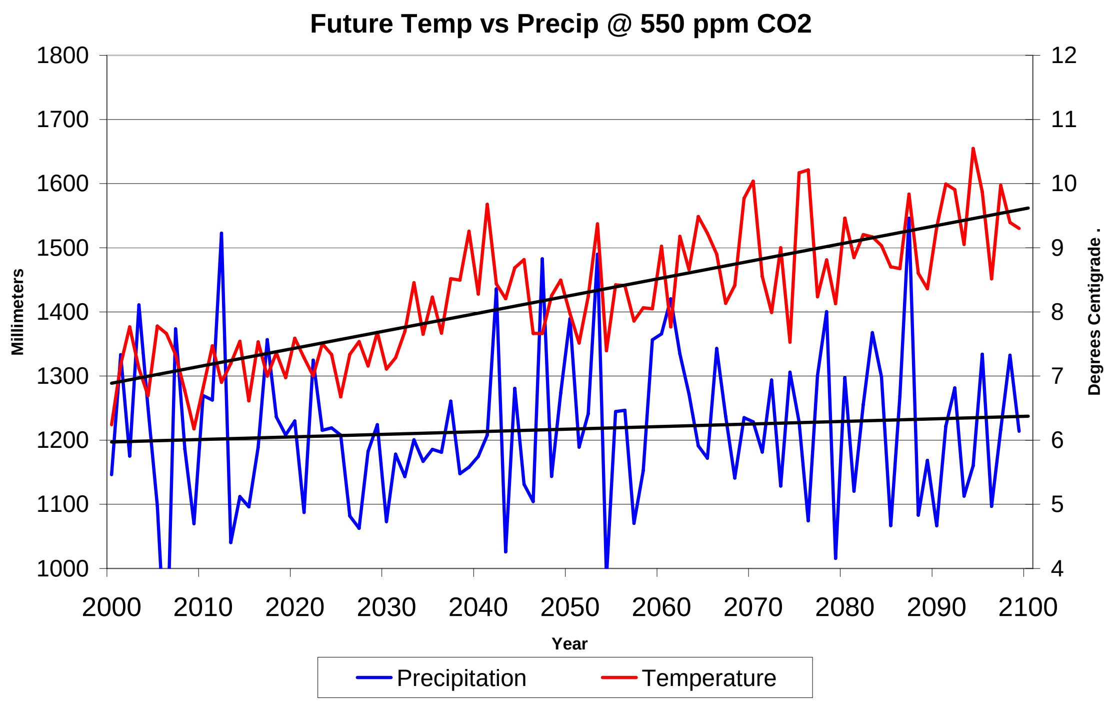

Figure 3 – Projected trends of precipitation and temperature for the CCMA data from the 550 ppm CO2 forcing scenario.

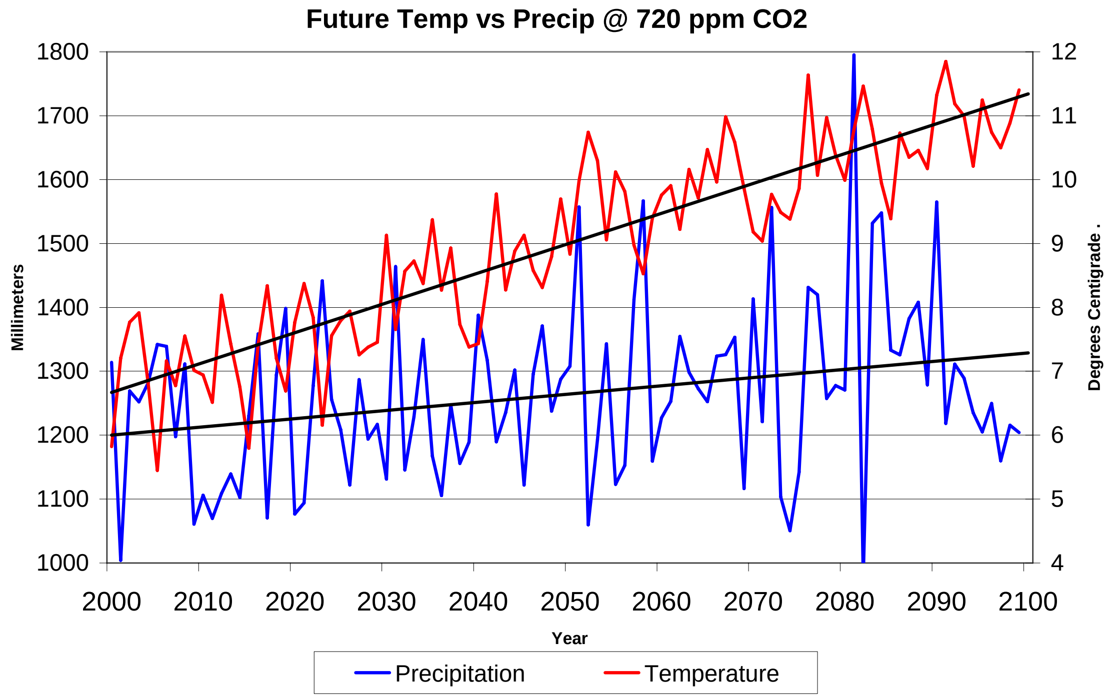

Figure 4 - Projected trends of precipitation and temperature for the CCMA data from the 720 ppm CO2 forcing scenario.

6.0 Results

6.1 Tree Species Forecasts

The results of the modeled growth relationships are described below. Each of the selected tree species is dealt with on an individual basis with the non-host insect species listed first, followed by the insect host species and lastly by the forecast made up of the individual Balsam fir chronology.

6.2.1 White Pine (Pinus strobus)

The white pine model was very sensitive to summer precipitation, January temperature and previous year's radial growth. Together they explained 71.5% of the current year's radial growth. The model had a high r-squared value explaining 70.88% variance between the modeled and actual data (Table 1). As evidenced in the calibration segment (Fig. 5), the model matched past growth well with a significant Pearson correlation value of 0.842 (Table 2). The verification segment in Figure 5 illustrates the strong predictive capability of the model which is further supported by a significant Pearson correlation of 0.681(Table 2) with past growth.

Table 1 – Explained variance values derived from a principal component analysis and the R-squared values derived from the regression analysis, both modeling past radial growth.

Tree Species	White Pine	Eastern Hemlock	Eastern White Cedar	Black Spruce	Red Spruce	Balsam Fir
Explained variance	71.5	76.7	76.1	69.8	59.6	60.3
R^2 value	70.88	75.28	77.27	66.01	61.22	50.70

When the model was run using the SRES B1 CGCM3 data (550 ppm) it produced a forecast for white pine that shows a similar growth trend over the 21st century compared to past radial growth (Fig. 5). The variability between the past and future curves differs significantly however. The standard deviation value of the 1900 –2000 past growth curve is 0.175 while that of the 2000 – 2100 forecasted curve is much smaller at 0.083 (Table 3).

Table 2 -Pearson Correlation values confirming relationships between past radial growth and the specific calibration and verification periods by species model.

Tree Species Models	White Pine	Eastern Hemlock	Eastern White Cedar	Black Spruce	Red Spruce	Balsam Fir
Calibration Period	0.842	0.868	0.879	0.563	0.744	0.664
Calibration P-value	0.000	0.000	0.000	0.000	0.000	0.000
Verification Period	0.681	0.527	0.685	0.653	0.703	0.462
Verification P-value	0.000	0.000	0.000	0.000	0.000	0.008

Table 3 -Standard deviation model results for 1900-2000 and 2000-2100 periods.

Tree Species	White Pine	Eastern Hemlock	Eastern White Cedar	Black Spruce	Red Spruce	Balsam Fir
Past Growth 1900-2000	0.175	0.208	0.168	0.187	0.224	0.221
550 ppm Forecast 2000-2100	0.083	0.179	0.166	0.083	0.137	0.093
720 ppm Forecast 2000-2100	0.097	0.199	0.224	0.089	0.120	0.093

The SRES A1B CGCM3 data (720 ppm) showed a marginally increasing radial growth trend toward the 2100 limit. Over the 100 year forecast, white pine radial growth increases by approximately 15% in the 720 ppm model (Fig. 6). This model also shows a decrease of variability from the past radial growth curve to the forecast curve. The standard deviation value for the 1900 –2000 segment is 0.175 compared to a 0.097 value for the forecasted growth curve (Table3).

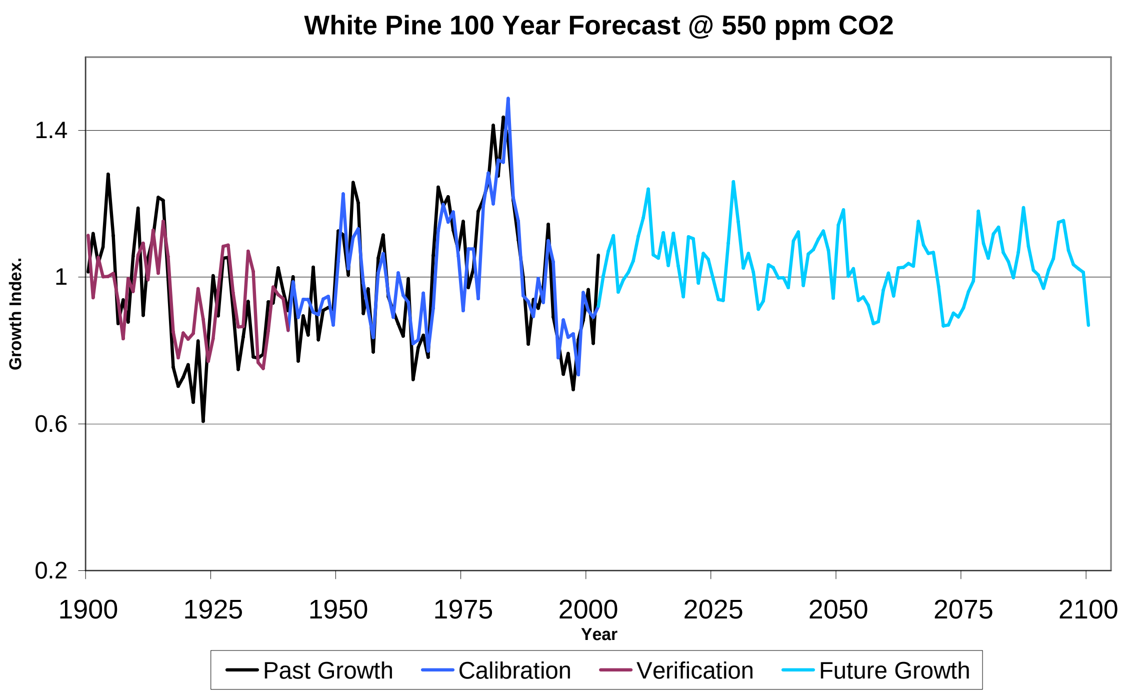

Figure 5 – White Pine model based on SRES B1 CGCM3 data. The model illustrates the past growth, calibration and verification periods as well as the forecasted future growth under the specific scenario tested.

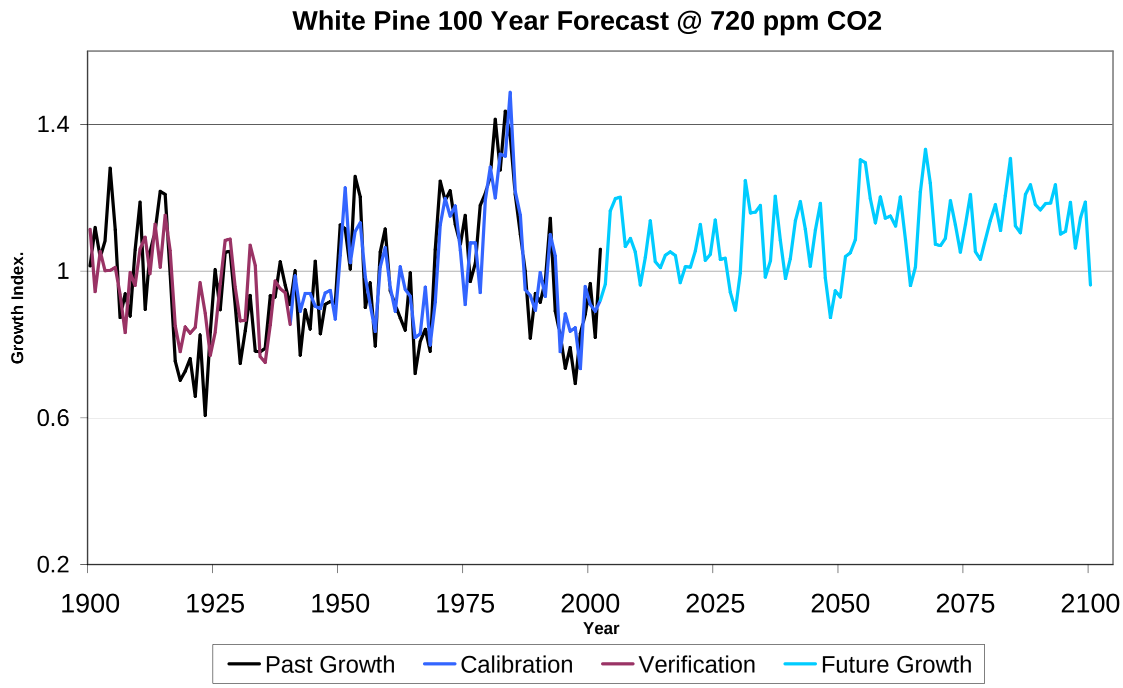

Figure 6 – White Pine model based on SRES A1B CGCM3 data. The model illustrates the past growth, calibration and verification periods as well as the forecasted future growth under the specific scenario tested.

6.2.2 Eastern Hemlock (Tsuga canadensis)

The eastern hemlock model was primarily driven by summer precipitation, September temperature as it related to the extension of the growing season and the previous year's growth. Together these factors explained 76.7 % of the current year's growth. The regression model had a high r-squared value explaining 75.28% of the hemlock variance (Table 1). The calibration segment of the model fit very well with the past radial growth of hemlock (Fig. 7). A Pearson's correlation test revealed a value of 0.868 when the past radial growth was compared to the calibration segment of the model (Table 2). The verification segment of the model in Figure 7 maintained a good fit with the past radial growth curve and a significant 0.527 value between the curves was determined with a Pearson's correlation test (Table 2).

When the model was run using the SRES B1 CGCM3 data (550 ppm) the output revealed an increasing growth rate trend over the 21st century resulting in a roughly 40% radial growth rise by the year 2100 (Fig. 7). Variance between past and future curves differed little in the hemlock model. Standard deviation values between 1900 – 2000 and 2000 –2100 were sequentially 0.208 and 0.179 (Table 3).

The SRES A1B CGCM3 data (720 ppm) showed an even larger radial growth increase of approximately 60% by the end of the 21st century (Fig. 8). Variance between past and future curves is less pronounced in this model and standard deviation values for 1900 –2000 are 0.208 compared with 0.199 for the 2000 –2100 period (Table 3).

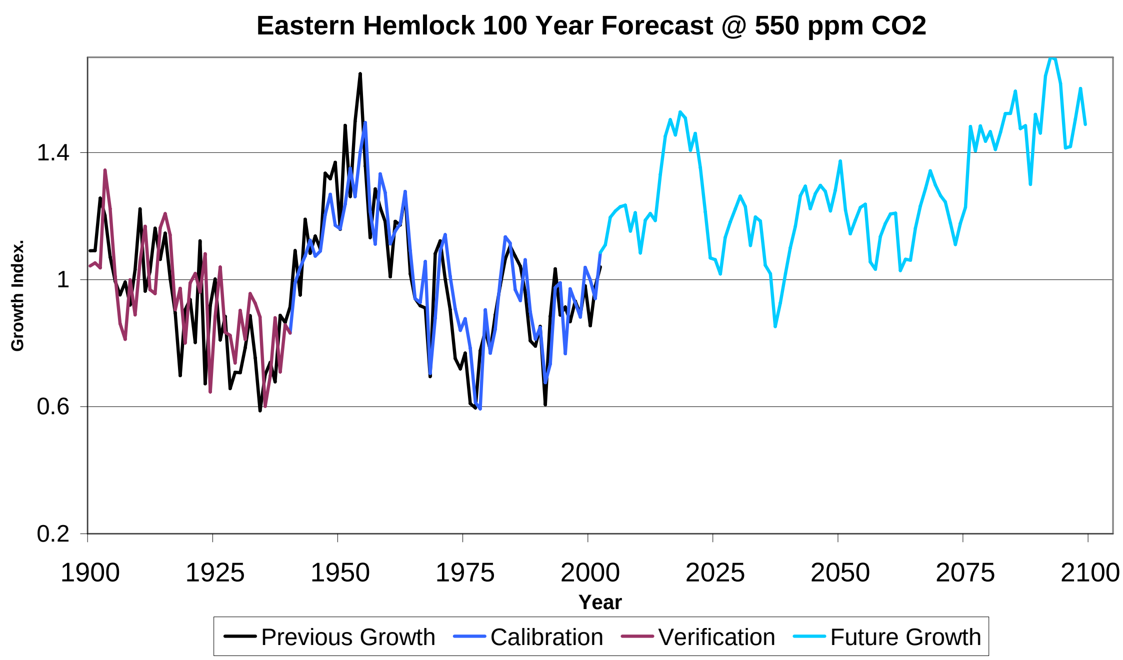

Figure 7 – Eastern Hemlock model based on SRES B1 CGCM3 data. The model illustrates the past growth, calibration and verification periods as well as the forecasted future growth under the specific scenario tested.

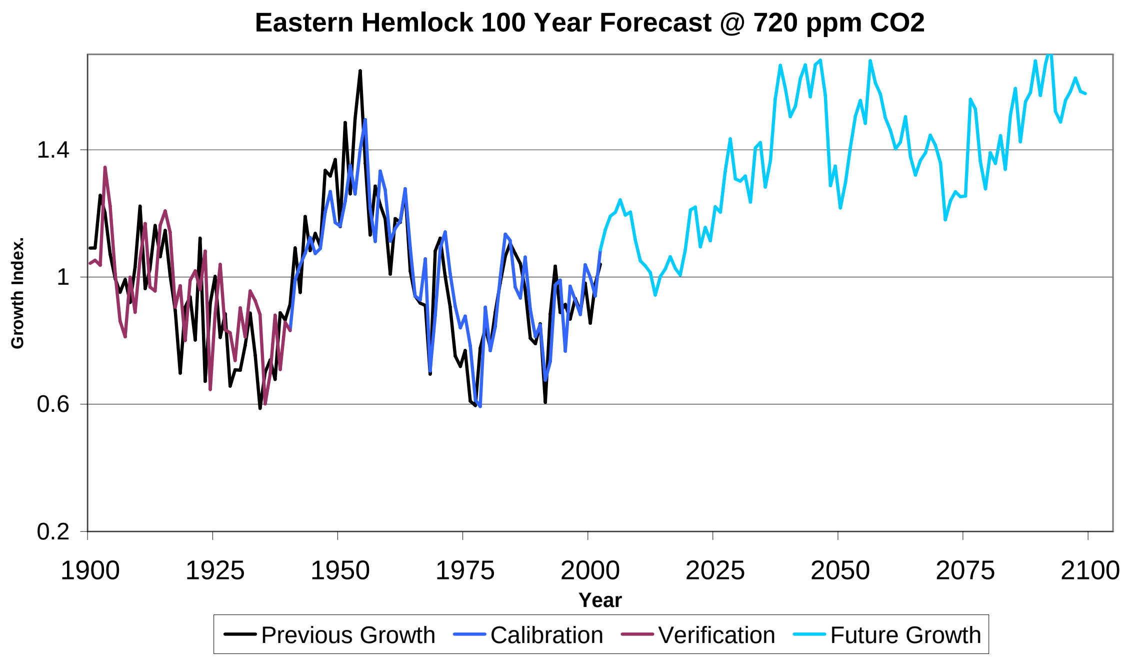

Figure 8 – Eastern Hemlock model based on SRES A1B CGCM3 data. The model illustrates the past growth, calibration and verification periods as well as the forecasted future growth under the specific scenario tested.

6.2.3 Eastern White Cedar (Thuja occidentalis)

The eastern white cedar model is negatively associated with July temperatures from current and previous years. The model is also driven by spring precipitation and the previous years radial growth, and together the climate and previous year's growth explain 76.1% of the current year's radial growth. The amount of variance explained by this regression model was very high with and r-squared value of 77.27 (Table 1). A comparison of the model calibration segment (Fig. 9) with the same period of past radial growth, identified a very high and significant Pearson correlation value of 0.879 (Table 2). In Figure 9 a Pearson correlation comparison between the verification segment and past radial growth produced a lower but still strongly significant 0.685 value (Table 2).

The SRES B1 CGCM3 data (550 ppm) ran through the cedar model produced an output showing a 50% decrease in radial growth by the end of the 21st century (Fig. 9). Variability between the past radial growth data and the forecasted radial growth was strikingly similar. Standard deviation tests produced a 0.168 value for the 1900 –2000 past data and an almost identical 0.166 value for the 2000 –2100 forecast at 550 ppm (Table 3).

The output produced from the SRES A1B CGCM3 data (720 ppm) showed a 75% reduction in radial growth by the year 2100 (Fig. 10). Variability between the 720 ppm model output and past radial growth were again alarming. Standard deviation tests showed a 0.168 value for the past radial growth of 1900 -2000 compared to a higher 0.224 value for the 720 ppm forecast output of 2000 – 2100 (Table 3), illustrating how deep the reduction in radial growth is forecasted to be .

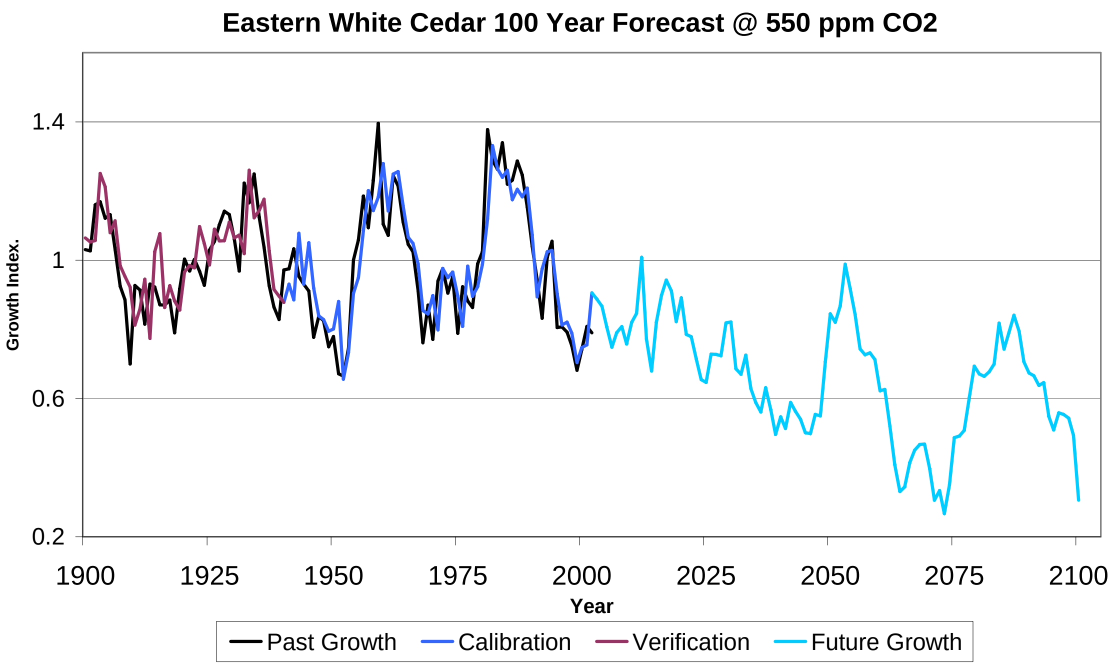

Figure 9 – Eastern White Cedar model based on SRES B1 CGCM3 data. The model illustrates the past growth, calibration and verification periods as well as the forecasted future growth under the specific scenario tested.

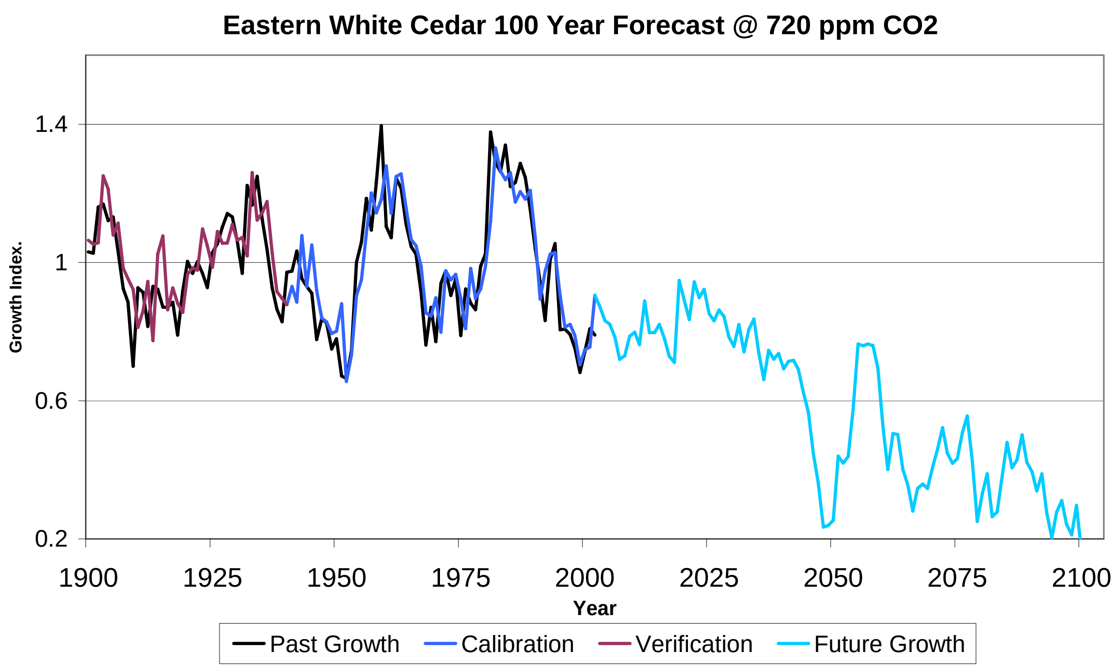

Figure 10 – Eastern White Cedar model based on SRES A1B CGCM3 data. The model illustrates the past growth, calibration and verification periods as well as the forecasted future growth under the specific scenario tested.

6.2.4 Black Spruce (Picea mariana)

The black spruce model was principally driven by warm winters, wet previous autumns and together with the influence from the previous year's radial growth on current year's radial growth, explained 69.8% of the variance (Table 1). Black spruce is the first of three species in this study in which radial growth has been strongly affected by spruce budworm. The r-squared values of the spruce budworm affected species are generally lower then that of the non-host tree species. An r-square value of 66.01 for this model explains less variance then the previous three models (Table 1). When comparing the past radial growth curve with the four calibration segments a Pearson correlation reveals a significant 0.563 value (Table 2). Although this figure is lower then the previous models the value for the three verification segments when compared to past radial growth increases to 0.653, and remains highly significant (Table 2). The calibration/ verification process concluded with the models illustrating dramatic radial growth decreases for the verification periods (Fig. 11), thus indicating that the climatic optimum for the two species of insect defoliators is also a negative radial growth influence for the tree species.

When the black spruce model was run using the SRES B1 CGCM3 data (550 ppm) we can see a 22% increase in radial growth by the model limit at 2100 (Fig. 11). Variance between past radial growth and forecasted radial growth at 550 ppm was quite different. A standard deviation test revealed a 0.187 value for the past radial growth data of the 1900 – 2000 period and a much lower 0.083 value for the forecasted curve of the 2000 –2100 period (Table 3).

The SRES A1B CGCM3 data (720 ppm) produced a comparable result as the 550 ppm data when processed through the black spruce model. A 28% rise in radial growth production is forecast to occur by the end of the 21st century using 720 ppm data (Fig. 12). Variance figures are also comparable to the 550 ppm model. A standard deviation comparison produced a 0.187 value for the past radial growth of the 1900 – 2000 period while the forecasted curve of the 2000 – 2100 period from the 720 ppm data set illustrated a 0.089 value (Table 3).

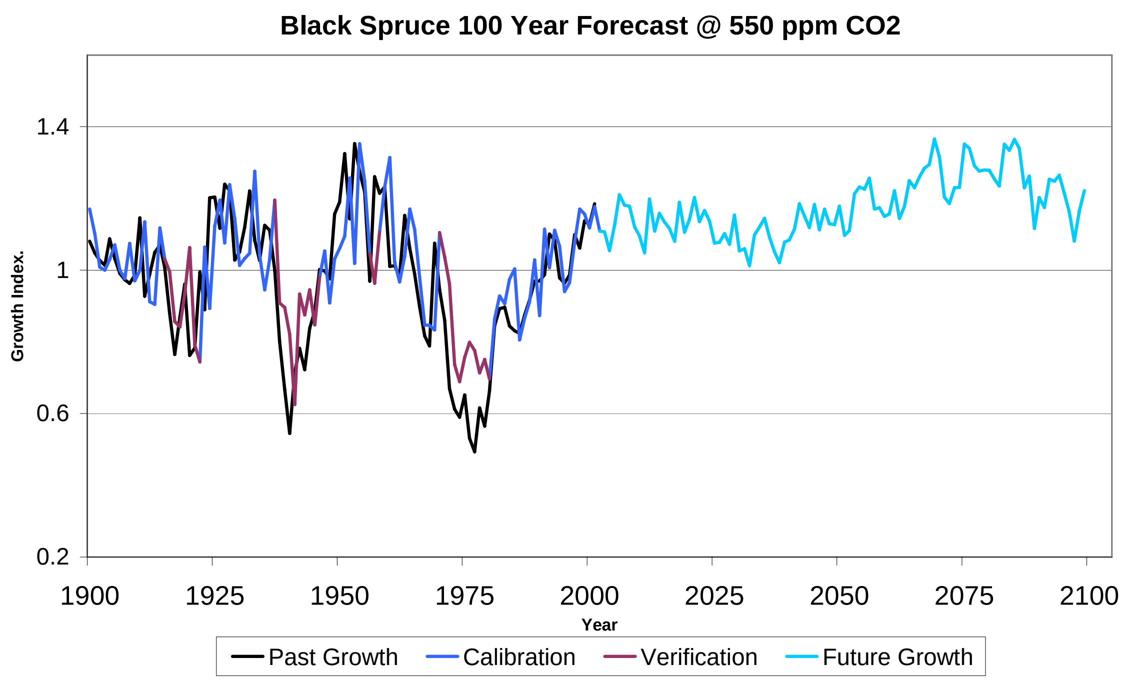

Figure 11 – Black Spruce model based on SRES B1 CGCM3 data. The model illustrates the past growth, calibration and verification periods as well as the forecasted future growth under the specific scenario tested.

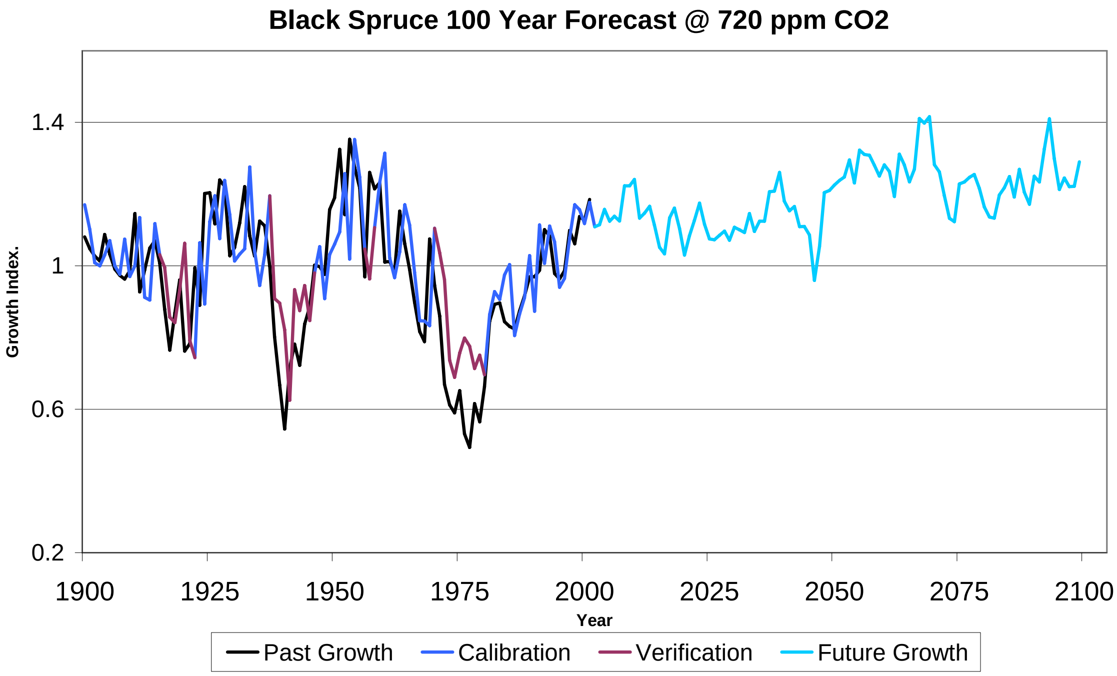

Figure 12 - Black Spruce model based on SRES A1B CGCM3 data. The model illustrates the past growth, calibration and verification periods as well as the forecasted future growth under the specific scenario tested.

6.2.5 Red Spruce (Picea rubens)

The red spruce model depends on a mix of temperature and precipitation. Warm winter temperatures are a very significant factor in the model, as well as, dry Mays and wet Julys. Past radial growth and climate have a 59.6% influence on current year's radial growth (Table 1). An r-squared value of 61.22 explains a lower amount of variance then previous models, as is to be expected considering the spruce budworm radial growth suppression periods (Table 1). When compared to past radial growth the five calibration segments in Figure 13 illustrate a 0.744 Pearson correlation value (Table 2). Also in Figure 13 the four verification segments combine to produce a 0.703 Pearson correlation when compared to the past radial growth, the highest of all models (Table 2).

The red spruce model produces a 40% increase in radial growth by the year 2100 when using the SRES B1 CGCM3 data (550 ppm) as evidenced in Figure 13. Variance in the 550 ppm model run is significantly different and shows a 0.224 value in the standard deviation test for past radial growth of 1900 –2000 that compares with a 0.137 value for the 550 ppm forecasted data of 2000 –2100 (Table 3).

When using the SRES A1B CGCM3 data (720 ppm) an extreme 50% rise in radial growth is predicted by the end of the 21st century (Fig. 14). Variance for the 720 ppm model is similar to that of the 550ppm model. The standard deviation comparison revealed a 0.224 value for past radial growth of 1900 – 2000 that contrasts from the 0.120 figure produced for the 720 ppm forecast curve of 2000 - 2100 (Table 3).

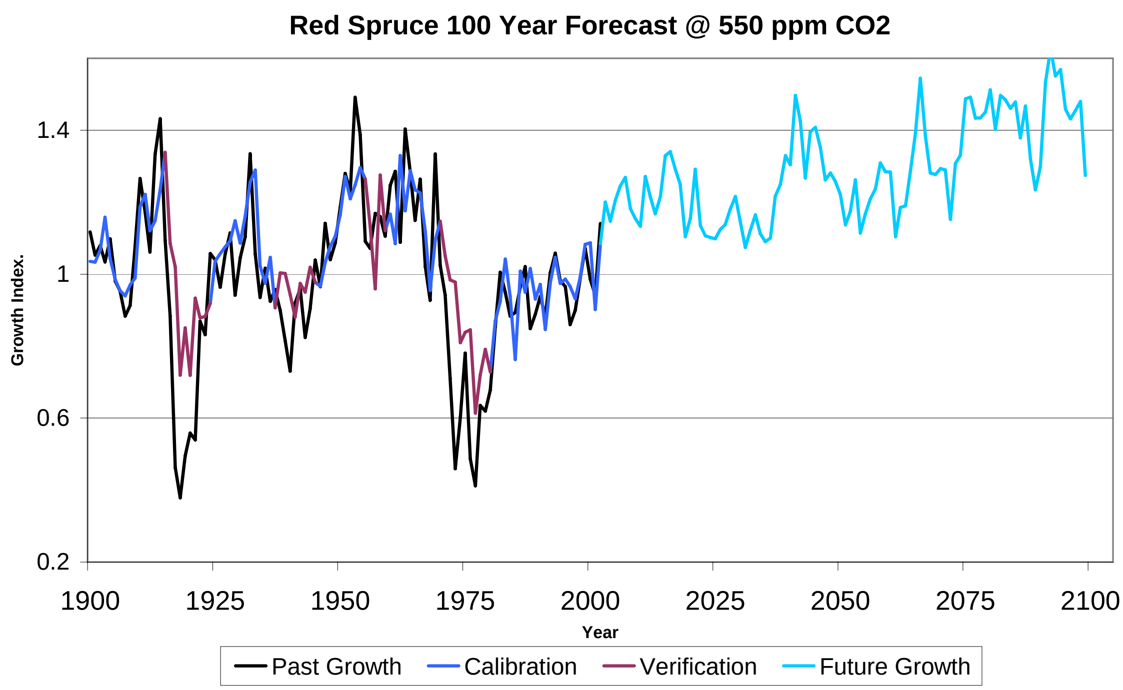

Figure 13 – Red Spruce model based on SRES B1 CGCM3 data. The model illustrates the past growth, calibration and verification periods as well as the forecasted future growth under the specific scenario tested.

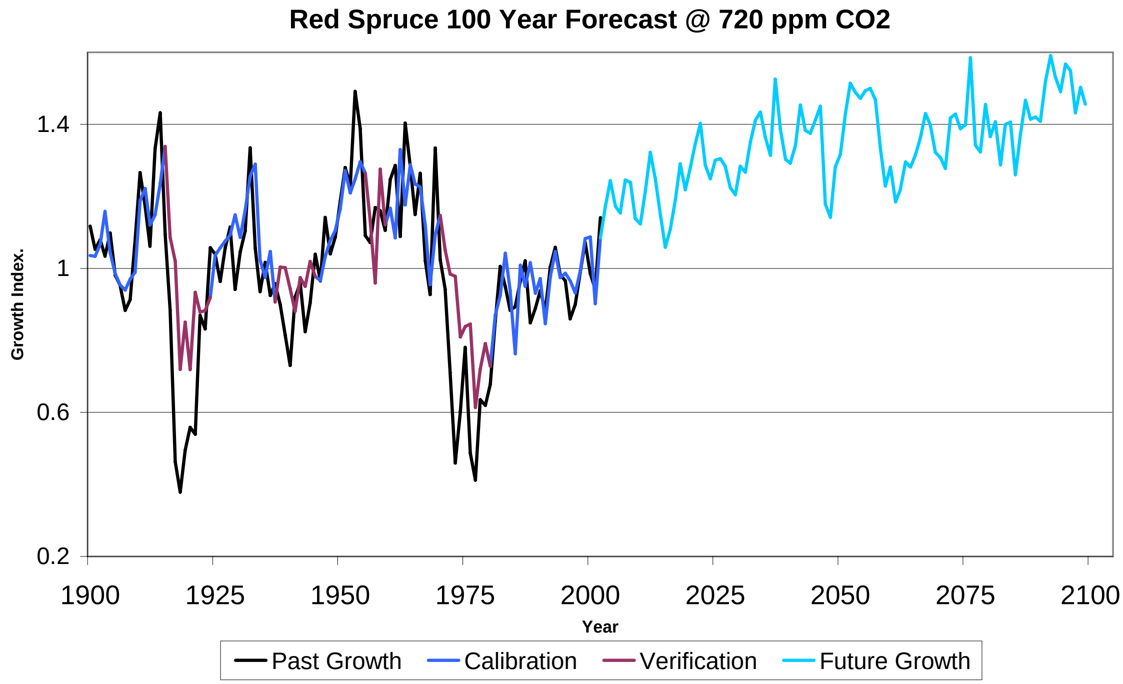

Figure 14 - Red Spruce model based on SRES A1B CGCM3 data. The model illustrates the past growth, calibration and verification periods as well as the forecasted future growth under the specific scenario tested.

6.2.6 Balsam Fir (Abies balsamea)

The balsam fir model is predominantly dependant on wet and cool previous July conditions, cold January temperatures and current year's radial growth, which can explain 60.3% of radial growth when combined with the effects of previous year's radial growth. This model had the lowest r-squared value of all the models, explaining only 50.7% of variance (Table 1). When the past radial growth (Fig. 15) was compared to the four calibration segments a Pearson correlation test revealed a lower but still significant 0.664 value (Table 2). The three verification segments showed a 0.462 Pearson correlation value when measured against past radial growth which was also the lowest correlated model verification, but still highly significant ($p > 0.008$) (Table 2).

The SRES B1 CGCM3 data (550 ppm) and the SRES A1B CGCM3 data (720 ppm) both produced a near average radial growth trend forecast over the 21st century when run through the balsam fir model (Fig. 15 and 16). Variance in past radial growth of 1900 – 2000 showed a standard deviation of 0.221which was significantly different then the 0.093 value that was calculated for both the 550 ppm and 720 ppm models covering the 2000 – 2100 period (Table 3).

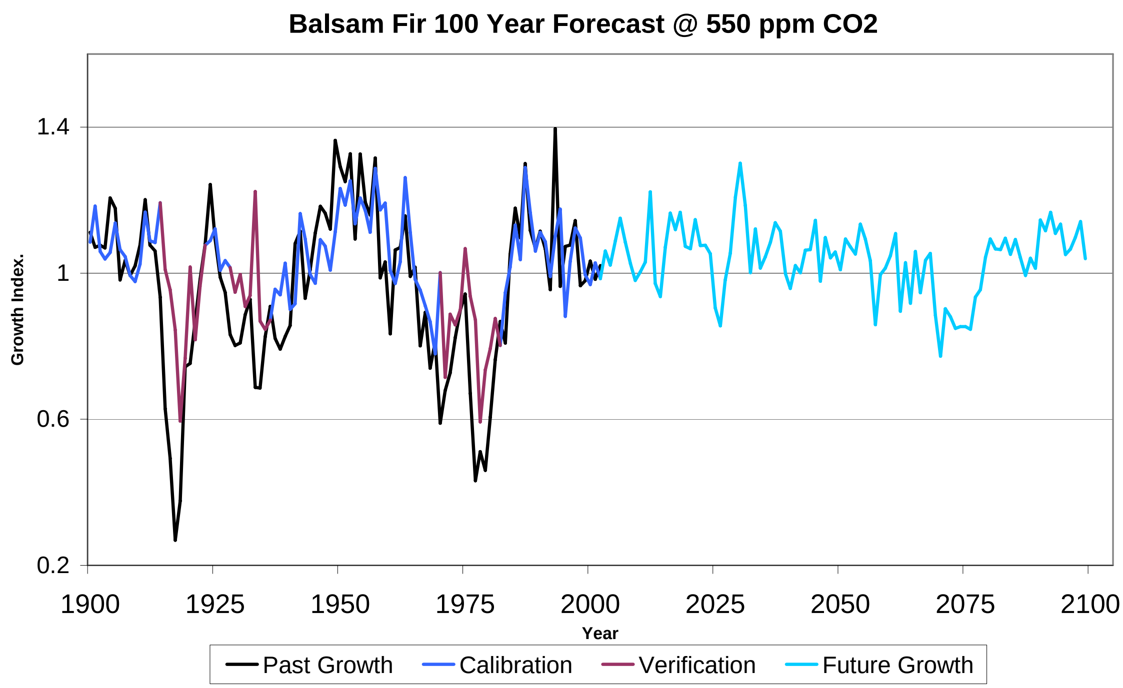

Figure 15 – Balsam Fir model based on SRES B1 CGCM3 data. The model illustrates the past growth, calibration and verification periods as well as the forecasted future growth under the specific scenario tested.

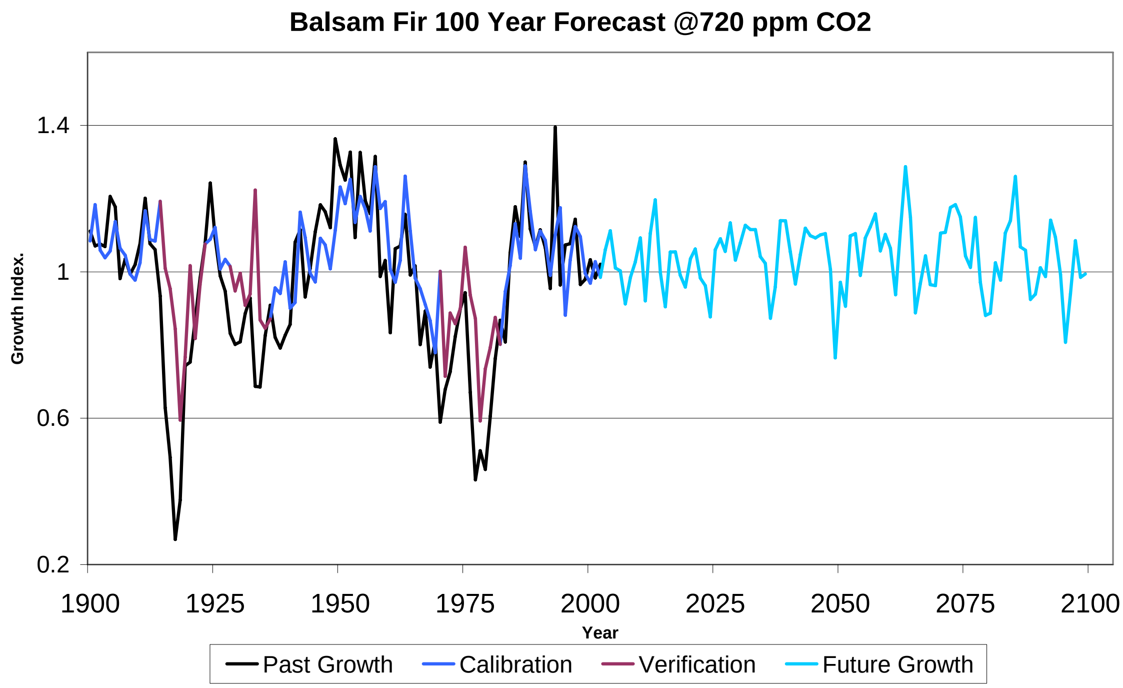

Figure 16 - Balsam Fir model based on SRES A1B CGCM3 data. The model illustrates the past growth, calibration and verification periods as well as the forecasted future growth under the specific scenario tested.

7.0 Discussion

7.1 Individual Species Discussion

Results of the above analysis will be discussed species by species.

7.1.1 White Pine (Pinus strobus)

The forecast for white pine is very reasonable considering the primary driver of radial growth is June, July and August precipitation. The CGCM3 data shows no real precipitation increase in the 550 ppm scenario and only marginal increases in the 720 ppm scenario (Fig. 3 and 4). This factor combined with the extended growing season is forecasted to result in white pine doing well under the forecasted environments. The forecast reflects this dependence on summer rainfall and shows stable radial growth outcomes for white pine over the next century. The decreased standard deviations of the forecast models for white pine may be caused by differences in the ranges of the historically recorded weather data compared with the forecasted CGCM3 data (see section 7.2), or simply because the model does not explain all variance. The CFS range relocation maps show the white pine range moving farther north but the Maritimes remains well within the extent of the range (McKenney 2006).

7.1.2 Eastern Hemlock (Tsuga canadensis)

The future for hemlock seems to be reliant upon summer precipitation and the extension of the growing season into September. The forecast CGCM3 550 ppm and 720 ppm scenarios both provide a continued supply of summer rain and an extension of the growing season which accounts for hemlocks large increase in radial growth rates as we near the 22nd century. This situation is somewhat analogous to past post-glacial warm periods. The height of the Hypsithermal Interval approximately 6000 B.P. was a time of peak temperatures and hemlock became the dominant coniferous species at that time (Mott 1974; Jetté & Mott 1995; Delcourt & Delcourt 1987). Although not completely understood, it is hypothesized and some evidence supports a hemlock looper outbreak that caused massive decline in hemlock (Bhiry 1995). If hemlock increases its numbers in the forest landscape the hemlock looper could again become a cause of concern. The hemlock forecast of this study is in agreement with the CFS future range maps (McKenney 2006).

7.1.3 Eastern White Cedar (Thuja occidentalis)

The forecast for eastern white cedar is very negative. Cedar is very detrimentally sensitive to hot July temperatures and requires heavy June precipitation. The CGCM3 data does not show a significant change in precipitation but only a significant temperature increase in the month of July which will create an unproductive environment for cedar. The 720 ppm scenario shows an extremely unprolific cedar population that will doubtfully have the competitive vigor to survive far into the 22nd century. The CFS range relocation maps show cedar having to migrate extreme distances to the north to survive under both SRES circumstances which is in agreement with the forecasts of this study (McKenney 2006).

7.1.4 Black Spruce (Picea mariana)

In this model warm winters and wet autumns are the principal drivers of growth. The forecasts showed increases in radial growth over the next century. The CFS range maps show black spruce migrating much farther north and disagree with the forecast models in this study (McKenney 2006). Perhaps the relatively minor radial growth increase will fail to keep this species competitive or insect populations may limit the southern extent of the range in the face of warming winters and better insect survival rates.

The situation with the black spruce model is influenced substantially by spruce budworm, as is the case with red spruce and balsam fir. The r-squared value and calibration correlation figures are lower than the non-host species of this study. Although the calibration segments of the model have specifically avoided the spruce budworm radial growth suppression periods it appears that artifacts of the insect defoliation periods have, possibly, altered the tree's radial growth response to climate enough that the model cannot explain as high levels of variance as seen in the non-host models. In other words the budworm seems to be affecting radial growth outside the growth reduction periods by, perhaps, altering the trees photosynthetic ability or energy storage capacity on a longer term scale then previously thought.

The extension of spruce budworm influence past the major growth suppression periods would introduce a non-climatic variable into the radial growth equation which was not available for the regression analysis. A second factor outside of the climatic variables is site related. All three black spruce sites used for this study were located on bog margins. The bog hydrology may be introducing another non-climatic variable that was not accessible in the regression analysis. The predominately wet soils of the bog margin may be limiting black spruce's dependence on precipitation or temperature as it relates to evapotranspiration.

One of the most interesting results of the modeling portion of the study is the verification period correlations with past radial growth of the spruce budworm host species. The models of the budworm affected species show an ability to strongly mirror the tree's radial growth when they are being severely inhibited by spruce budworm defoliation. The models are based purely on climatic variables yet they show correlation figures that are on par with those of the non-host species for the modeled verification segments. This would indicate that the climatic situation that favours spruce budworm must have an inverse relationship regarding radial growth, thus allowing the models to closely predict radial growth during spruce budworm defoliation events.

Although the models appear able to show radial growth reductions during spruce budworm outbreak periods they fail to do it on the same magnitude as experience by the trees. It is these differences in the magnitude of radial growth reductions that seem to be the reason for reduced variance in the forecasted models of the spruce budworm affected species (Table 3). The models are reproducing radial growth reduction periods due to climatic influence but they cannot predict if budworm will continue to cause severe defoliation outbreaks during those periods in the future. The difference in radial growth magnitudes compared to modeled, climatically driven radial growth reductions may account for the differences in decreased standard deviation values for future radial growth in the host species models compared to non-host models. In either case, the introduction of insect defoliators into the radial growth trends of trees is very complex.

7.1.5 Red Spruce (Picea rubens)

Red Spruce radial growth is driven by warm winter temperatures, dry May weather and wet July weather. As temperatures increase our winter weather will become warmer favouring red spruce. The forecasted growth reflects this seasonal relationship and shows red spruce exceeding radial growth rates of the past making it a much more competitive species. This future scenario disagrees with the CFS range response to climate change (McKenney 2006). Perhaps red spruce will become more competitive with other tree species but more susceptible to insect attack which could limit the southern extent of the specie's range.

7.1.6 Balsam Fir (Abies balsamea)

The forecast for balsam fir illustrates a continued average rate of growth over the 21st century. Fir's dependence on cool, wet previous Julys and cold Januarys, as well as, a number of other less significant factors leave fir with a minimal response to forecasted changing climates. The CFS range models show fir moving out of the Maritime Provinces and that scenario is reasonable considering fir's susceptibility to many different forest insects and pathogens that may move into a warmer Maritime environment (McKenney 2006). This also agrees with the notion that fir is noted for following the Polar Frontal Zone (PFZ) since the last period of glaciation in search of greater amounts of precipitation (Delcourt & Delcourt 1987).

With the lowest r-squared values of the models, the lowest Pearson correlation relationships, and the largest difference between past and future standard deviations, this model remains problematic and may not be presenting a completely accurate forecast. Balsam fir has been greatly impacted by spruce budworm and encounters the same difficulties in forecasting as black spruce and red spruce. Like black spruce, the single fir site the model is derived from was found on the margin of a bog. This could introduce some of the same complications as was discussed in the black spruce situation. Balsam fir appears to be affected by these anomalous, non-climatic ecological influences to a greater degree then the more robust black spruce and red spruce master chronologies, leaving this forecast in a more suspect light.

7.2 Predictive Limitations of Forecast Models

The forecast models created in this study are obviously limited by the predictive accuracy of the CGCM3 data. Global Climate Model data is an evolution in progress, constantly being updated, redefined, and constantly being fed better and more spatially continuous data. As such, the future predictions of this study need to be qualified by ability of the modeled data to forecast scenarios set forth by the IPCC. As future scenarios change, and new generation of models are produce, the forecasts derived for future radial growth will also need to be updated.

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 one hundred years of radial tree growth in comparison to the past one hundred years of historical weather data. During this one hundred year period there has been much climatic variability but there are certainly future forecasted climatic maximums of both temperature and precipitation that are outside of the range of the past climates. The models are completely based on the relationship of past radial tree growth to the experienced environmental variability. 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 100 years and could therefore be missing from the forecast models.

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 quickly disperse can not be taken into account in our models.

8.0 Conclusion

Forecast models of potential future radial growth have been developed for six coniferous tree species. Using the science of dendrochronology master chronologies were constructed for each species as a record of past average growth. Radial growth - climate relationships were produced using historical weather data in a regression analysis which explained a range of variance from a low of 50.7% in balsam fir to a high of 77.27% in eastern white cedar. Forecasts based on two scenarios of coupled global climate model outputs were then produced covering the 21st century.

There was no particular positive or negative aggregate direction of future radial growth among the forecasts. The eastern hemlock model forecasts the best performance realizing a 60% increase in radial growth by the year 2100 under the more extreme CGCM forecast. Hemlock should take advantage of a lengthened growing season and may potentially reacquire some of its former dominance achieved during the Hypsithermal Interval. Eastern Cedar failed to prove its capacity to remain competitive under future Maritime climates. Cedar realized a 75% reduction in radial growth by the end of the 21^{st} century under the more extreme CGCM forecast. Warming summer temperatures appear to cause difficulty for the species and should cause it to seek cooler environments to the north.

The final outcomes of the forecasts were not without potential problems. Two species of spruce and the balsam fir were all severly affected by spruce budworm during the past 100 years which caused complex problems in accessing their climatic relationship. To further exacerbate those problems the only black spruce and balsam fir that could be found, were sampled on bog margins which introduced a new set of non-climatic factors into the data. The extra factors, most likely to do with bog hydrology, may prove to further obscure the climatic associations this study looked to find.

Along with limitations of the CGCMs data itself, there is an uncertainty associated with ecological thresholds that may have escaped the model building process. But we feel that given these limitation, the biologically based modeling that we have conducted on the tree species in our study, on trees that are currently rooted in place and are functioning as a forest, represent the best future forecasts that have been produced to date for trees in the Fundy Model Forest region. We also feel that the results are promising enough to merit further research in this direction.

9.0 References

Bhiry, N. & Filion L., 1996. Mid-Holocene Hemlock Decline in eastern North America Linked with Phytophagous Insect Activity. *Quaternary Research* 45, 312-320

Brown, C. E. 1970. *A Cartographic Representation of Spruce Budworm Infestation in Eastern Canada, 1909-1966.* Department of Fisheries and Forestry, Ottawa Canadian Forestry Service Publication No. 1263

Clayden, S. R. 2000. History, Physical Setting, and Regional Variation of the Flora. In Hinds, H. R., *Flora of New Brunswick* (pp 35-73). Fredericton, NB: Biology Department, University of New Brunswick.

Delcourt, P. A. & Delcourt, H. R. 1987. *Long-Term Forest Dynamics of the Temperate Zone.* New York : Springer-Verlag

Iverson, L. R. & Prasad A. M. 2001. Potential Changes in Tree Species Richness and Forest Community Types following Climate Change. *Ecosystems 4: 186-199*

Jetté, H. & Mott, R. J. 1995. Vegetation and climate Maritime Canada 6000 year BP : a synthesis. *Géographie physique et Quaternaire* 49: 141-162

Kettela, E. G. 1983. *A Cartographic History of Spruce Budworm Defoliation 1967 to 1981 in Eastern North America.* Environment Canada, Canadian Forestry Service, Maritime Forest Research Centre, Fredericton, N.B., Catalogue No. Fo46-13/1983

Laroque, C., 2005. The Dendroclimatological Potential of Five Conifer Species from Southwestern Nova Scotia. *Program and abstracts from the Atlantic Division of the Canadian Association of Geographers*, St. Johns, NFLD October 14-16, 2005.

McKenney et al., 2006. *Canada's Plant Hardiness Site – Going Beyond the Zones.* Natural Resources Canada, Canadian Forest Service, Landscape Analysis and Applications Section. Website visited March 19,2007: http://www.planthardiness.gc.ca/

Mott, R. J. 1990. Sangamonian forest history and climate in Atlantic Canada. *Géographie physique et Quaternaire* 44: 257-270

Power, R. G. & Matson, B. E. 1995. *Ecological Land Classification of Southeastern New Brunswick.* Natural Resources Canada, Green Plan, Ecological Land Classification Initiative, and New Brunswick Department of Natural Resources and Energy, Hampton, N.B.

Ritchie, J. C. 1987. *Postglacial Vegetation of Canada.* Cambridge, UK: Cambridge University Press.

Schweingruber, F. H., 1996. *Tree Rings and Environment Dendroecology.* Birmensdorf, Swiss Federal Institute for forest, Snow and Landscape Research. Berne, Stuttgart, Vienna, Haupt. 609pp.

Woodley, S. et al. 1998. *State of the Greater Fundy Ecosystem.* Greater Fundy Ecosystem Project, University of New Brunswick, Fredericton, N.B.