AN INVESTIGATION OF LANDSCAPE EVOLUTION IN MALIGNE PASS, JASPER NATIONAL PARK.

MAD Lab Report 2005-06

By

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Abstract

Landscape evolution was studied in Maligne Pass, Jasper National Park by evaluating changes in treeline at the alpine-subalpine boundary. These changes were linked to local climate parameters in order to create a relationship between tree growth and climate. This relationship was taken further to predict future growth in the area for the next century. This was done using climate forecasts from the Second Generation Coupled Global Climate Model (CGCM2). All trees, seedlings and sapling were surveyed within a 10m by 300m plot of a South facing slope in the treeline ecotone. *Abies lasiocarpa* (Hook.) Nutt. was the dominant species, and individuals were sampled by both increment borer and destructive sampling. The changes in landscape were found to coincide with the warming period following the Little Ice Age. Important establishment periods occurred between 1974 and 1983 as well as between 1934 and 1943. July temperature and the previous year's growth were found to significantly affect tree growth. Temperature and precipitation levels are predicted to remain stable over the next 100 years in the Maligne Pass area based on predictions of the CGCM2. For this reason, the modeled future growth of subalpine fir showed no significant change. The dendrochronological analysis revealed no drastic change in treeline position suggesting minimal impacts on the local wildlife and ecosystem.

Keywords:

Abies Lasiocarpa, climate change, coupled second generation global climate model, dendrochronology, Maligne Pass, treeline ecotone, tree-ring analysis

Introduction

Maligne Pass is a remote area in Jasper National Park. It offers a particularly interesting ecology as the slopes of the Rockies house the treeline ecotone, which is defined as transitional zone between the alpine forest and tundra biomes. This zone is delimited by the timberline and the tree limit. The *tree limit* is the highest elevation at which any tree can be found, the *timberline* is the limit of continuous canopy forest and the *treeline* is the highest elevation at which erect trees (≤1.5m) are found (Kavanagh, 2004). The treeline ecotone is significant because its vegetation is particularly sensitive to fluctuations in environmental conditions. This is due to the fact that the flora occurs at its autecological limit. Treeline ecotones are thus particularly vulnerable to climate change (Brubaker 1986). Maligne Pass was chosen as a study site because of its unique ecology as well as the history associated with the area.

In 1907, Mary T. S. Shäffer, one of the first renowned women explorers in the Canadian Rockies, set out to find a lake known by the Stoney Indians as the Chaba Imne. She travelled through Maligne Pass following a hand made map to find this lake which she later renamed Maligne Lake. Since she took many photographs during her voyage, our intent was to relocate one of these areas and rephotograph it to determine if the landscape in the area had since changed.

According to Brubaker (1988) vegetation shows differing responses to climate variation based on the temporal scale in question. Long-term variations (10,000 to 100,000 years) induce major displacement of species as well as genetic adjustments through natural selection. Intermediate time scale variations (2,000 to 5,000 years) include adjustments in species' range as well as some evolutionary changes. Short-term variations (up to 500 years) generally occur within a tree's life-span and are expressed as phenotypic changes in already established tree as well as changes in reproductive and establishment rates. In terms of a decadal time scale, the effects of climate variations are less clear. A portion of this project was then dedicated to evaluating the variations that occur within a tree stand over such a time scale.

Previous work by Kearney and Luckman (1983) pertaining to Holocene timberline fluctuations in Jasper National Park provides a detailed record of fluctuations during the last 8700 years. They suggest that between 8700 and 5200 years ago the timberlines were actually much higher than at present but saw important periods of recession (6700 to 5900 and 8700 to 7000 years ago). Since 5200 years ago timberline recession has been ongoing, attaining the lowest position some time after 500 years ago.

A subsequent study by Kearney and Luckman (1987) reconstructed the vegetation and climatic changes of the Holocene in Maligne Valley, Japer National Park. According to the earliest sediment records dating from 8500 years ago, they suggest that subalpine forest has since characterized the site. The more modern features of discontinuous subalpine forest and dwarfed-tree dominated damp meadows and fens only emerged in the last 1300 years. A warmer episode extending from 2600-3400 years ago was also identified.

A study of treeline dynamics was conducted by Trudy Kavanagh (2000) in Sunwapta Pass. This study focussed on reconstructing the area's history in terms of treeline dynamics associated with climate variability over the past 400 years. Because both sites are in close proximity, it was hypothesized that this study would yield similar results. Her study involved two slopes (north and south facing) while this study only encompassed a single south facing slope. Kavanagh suggested that establishment (seed germination and long-term survival of seedlings and trees) always occurs when temperatures exceed 1.0 ºC above the mean summer temperatures from 1961 to1990. Overall, it was found that establishment has increased in the past century; the most important periods occurring in the 1920's, the 1950's and especially in the 1960's. Again, similar trends were expected to emerge from the Maligne Pass data. At the landscape level, Kavanagh found that the treeline has advanced over time. Her general conclusions propose that changes in treeline position are dependant on seedling growth rates. Rapid growth translates into rapid upslope migration of the treeline while slower growth rates generally cause lags between climate events and treeline shifts. Finally, Kavanagh's work supported the hypothesis that had previously been put forward by several researchers, including Kullman (1986) and Shiyatov (1993), stating that treeline advance is generally associated with warmer temperatures.

Furthermore, research conducted by Rhemtulla *et al.* (2002) also presented interesting insight as they examined 80 years of vegetation change in the montane ecoregion of Jasper National Park (1915-1997). Even though Maligne Pass is generally considered a subalpine ecoregion, the overall findings relating to climate variations are assumed to be comparable between sites. According to Rhemtulla *et al.* there was a greater amount of change in landscape vegetation cover from 1915 to 1949 then from 1949 to the present. These changes include increases in stand density and crown closure. It was also found that vegetation has become more homogenous over the last 80 or so years.

As indicated by the studies discussed, there was much evidence to support that Maligne Pass would show shifts in treeline position. Our focus was then to discern how the landscape has changed. We attempted to clarify why theses proposed changes have occurred by relating them to variations in local climate. This created a pattern of tree growth based on the past climate record. We extended this pattern of tree growth to the future in order to predict tree establishment over the next 100 years based on future climate predictions from the Canadian Centre for Climate Modeling and Analysis (CCCma, 2005).

Similar work has been done by Laroque and Smith (2003) in an attempt to predict the radial-growth pattern of five high elevation species on Vancouver Island, British Columbia. Future climate was modeled using forecasts generated by the second-generation coupled general circulation modeled (CGCM2). The results showed that each species reacted differently to future predictions. This study did not encompass the dominant species present at our study site (*Abies lasiocarpa* (Hook.) Nutt.) therefore it was difficult to make predictions about the expected outcome for Maligne Pass based on these findings.

This project is believed to have practical significance as it predicts the possible effects of climate change. The results highlight the anticipated implications for wildlife in the area, which is of particular relevance for Jasper National Park as it is home to 53 species of mammals all of which depend on its diversity of habitats. A variety of small mammals and grizzly bears are known to inhabit the area of Maligne Pass.

To summarize, the goals of this research project were as follows; to determine how the landscape in Maligne Pass has changed in the past 100 years, to determine why it has changed by relating changes to climate variations, to predict future change based on different climate change scenarios and to discuss possible implications this may have for wildlife and ecosystems.

Study Site

The study site was located in Maligne Pass, Jasper National Park, Alberta (Figure 1). It was sampled on July 13th, 2004. Its exact location was 52° 29.604' N latitude and 117° 26.293'W longitude. The sampled area represented 3000m^2 of a south facing slope that showed variation in both tree density and vegetation cover. This site included both an upper and lower treelimit as well as two small creeks (see Figure 2). The elevation was 2160 ± 5.8m at the bottom of the slope and reached a maximum elevation of 2235 ± 5.8m. The dominant species was subalpine fir (*Abies lasiocarpa)* with a very minimal amount of engelmann spruce (*Picea englemannii* Parry ex Engelmann).

Figure 1 Maligne Pass study site. (Photo by Laroque, C.P. 2004)

Methods

Site Selection

The selection of a study site involved finding a location with both an upper and a lower tree limit. A gentle slope angle was also an important characteristic. We tried to locate an area with infilled regions and tree islands so that it presented similarities to one of Kavanagh's (2000) study sites. This allowed for cross study comparisons.

Field methods

A 300 metre line transect was laid down starting at the bottom of the slope using a standard compass and measuring tape. Flagging tape was used to demark 5m intervals along this transect. A grid system was established by creating $5m^2$ plots running along both sides of the central transect. Each individual tree was mapped and classified as either seedling (< 0.5m), sapling (≤ 0.5m and ≥ 1.5m) or tree (>1.5m). Measurements of diameter and height were obtained for each individual. Diameter was measured with a diameter at breast height (dbh) tape. Height was measured using a measuring tape for seedlings and saplings while a clinometer was used to measure taller trees. Sampling was done in accordance with a Jasper National Park research permit (permit no. 2004-026)). An increment borer was used to obtain samples from the base of the trees to accurately determine their age. These trees were chosen randomly within the sample site. The cores were subsequently placed in plastic straws and labelled for safe return to the laboratory. An additional 60 samples, chosen randomly from seedlings and saplings, were obtained by destructive sampling as they were cut down at the base. Finally, a slope analysis of the site was conducted using a clinometer and a measuring tape. This allowed us to detect and to measure changes in slope angle.

Repeat Aerial Photographs

Locating previously photographed areas proved to be a very challenging task; consequently, historical aerial photographs (1949, 1979 and 1993) encompassing the chosen study site were located. These were obtained from the National Air Photo Library in Ottawa. Basic visual assessments were used to directly compare the landscape changes over time.

Sample Preparation and Analysis

The core samples were left in their straws to dry and then were glued into slotted mounting boards. The disks were placed in a drying oven overnight at 40ºC to allow them to dry. All samples were sanded to a high polish to reveal the ring pattern. The annual rings from the core samples were measured to 0.001mm with a Velmex system. The disk samples were aged but the ring pattern was not analysed because the harsh growing conditions at high altitude often cause sporadic growth patterns in young trees. Such data would make it very difficult to find a single unified growth pattern.

The age data from the disks and cores were used to create a linear regression relating diameter and age as well as height and age in order to be able to determine the age of all trees in the sample plot. This allowed the creation of an age distribution for the site.

The ring measurements were entered in a statistical program, COFECHA (Version 3.0, Holmes 1999), to determine how well the different growth patterns correlated together. The program output allowed us to determine if all the trees were showing the same growth pattern and to identify and eliminate outliers. A data set of subalpine fir from the University of Victoria Tree Ring Lab (UVTRL) archive (99Y300) was compared to the collected data set (04ABL300). This data set was from the Hilda Rock Glacier which is located a few hundred metres from Kavanagh's (2000) site. The comparison of SAF data sets was done to determine if the growth pattern observed in Maligne Pass was similar to that observed in Sunwapta Pass (Kavanagh, 2000). This comparison also allowed us to determine if the two data sets could be amalgamated to extend the Maligne Pass ring pattern record further back in time, and to increase the sample size.

Next, a master chronology was created using a program called ARTSAN (Cook, 1999). This standardized the growth values to give a single unified growth pattern, the master chronology, for subalpine fir. The master chronology was then used to generate a relationship with local climate.

Local Climate data

The climate data from various stations near the study site (Table1.0) were obtained from Environment Canada (Climate Monitoring and Data Interpretation Division, 2002). The stations were compared to the Maligne Pass site to determine which station would most accurately represent the climatic conditions of this particular area.

Table 1.0 Adjusted Historical Canadian Climate Data from Environment Canada.

Station Name	Latitude	Longitude	Elevation (m)	Temperature record range	Precipitation record range
Banff	51.18	115.57	1388.79	1895-2003	1895-1994
Edson	53.58	116.46	921	n/a	1920-1998
Entrance	53.37	117.70	991	1917-2001	n/a
Jasper	52.83	118.07	1061	n/a	1936-1995
Rocky Mnt. House	52.43	114.43	982	1915-2001	1917-1994

Creating the Growth-Climate Relationship

The establishment of a tree growth-climate relationship was done using a software program called PRECON (Fritts 1994). It performed a principle component analysis of the growth data and identified which climate parameters significantly affected tree growth.

Generating Future Climate and Forecasting Future Growth

Future climate data was generated using a global climate change model. Such a model simulates the effects of a wide variety of parameters that simultaneously act on climate. We used the results of the second generation coupled global climate model (CGCM2) (Flato and Boer, 2001; Flato *et al.*, 2000; Flato and Hibler, 1992; Gent and McWilliams, 1990) obtained from the Canadian Centre for Climate Modelling and Analysis (CCCma, 2005). The two metre screen temperatures were obtained in the form of monthly means from 1900 to 2100. The daily precipitation data was obtained for that same time frame and converted to monthly values.

Using SPSS 10.0, we applied a forward step-wise multiple regression analysis to the CGCM2 generated data from 1900 to 2000. This created a mathematical relationship between the various parameters affecting radial tree growth. The model was tested against the actual growth trend of SAF to verify that future growth could indeed be predicted using this particular data. The relationship was then extended into the future by applying the mathematical equation to the future data (2000-2100).

Results

Field Mapping and Sampling

Overall, 534 individuals were mapped and measured. A total of 55 trees were sampled within the site using an increment borer. An additional 60 seedlings and saplings were destructively sampled.

The tree distribution at the sample site showed varying densities along the slope. The highest density was found near the middle of the site while the extremities had lower densities (Figure 2).

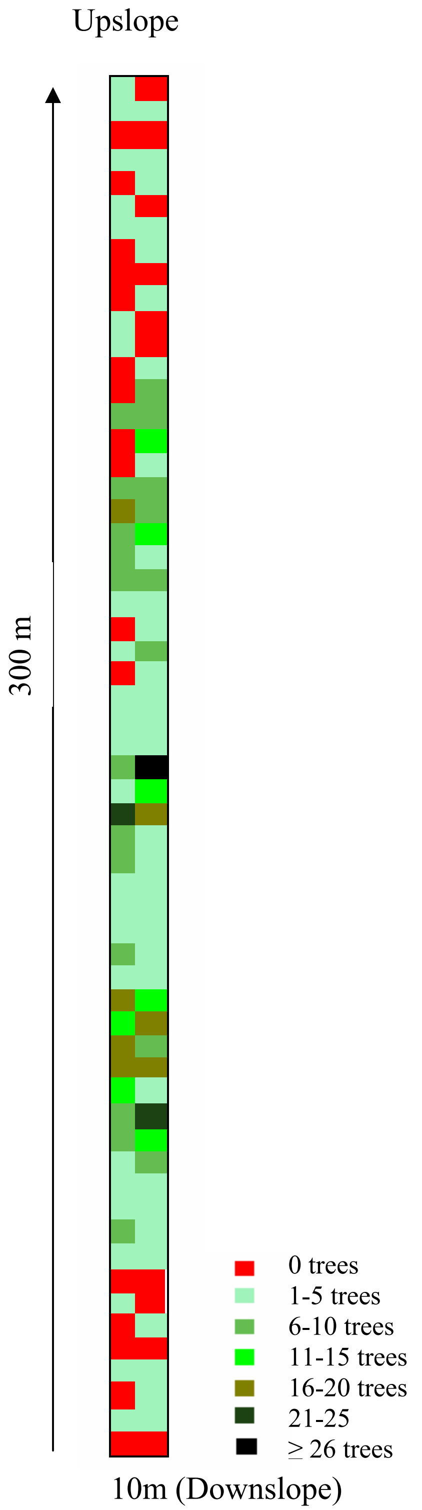

Figure 2 Density map of seedling saplings and trees at Maligne Pass showing the number of individuals per 5x5m plot.

Slope analysis

The analysis of the slope revealed where the incline was steepest. This occurred between the 150 and 200 metre marks (Figure 3) where the slope incline reached a maximum of 40 degrees. The slope was relatively flat at the bottom of the study area as well as at the top. The dip in slope observed at the 75 metre mark coincided with a small creek that was flowing through the study area.

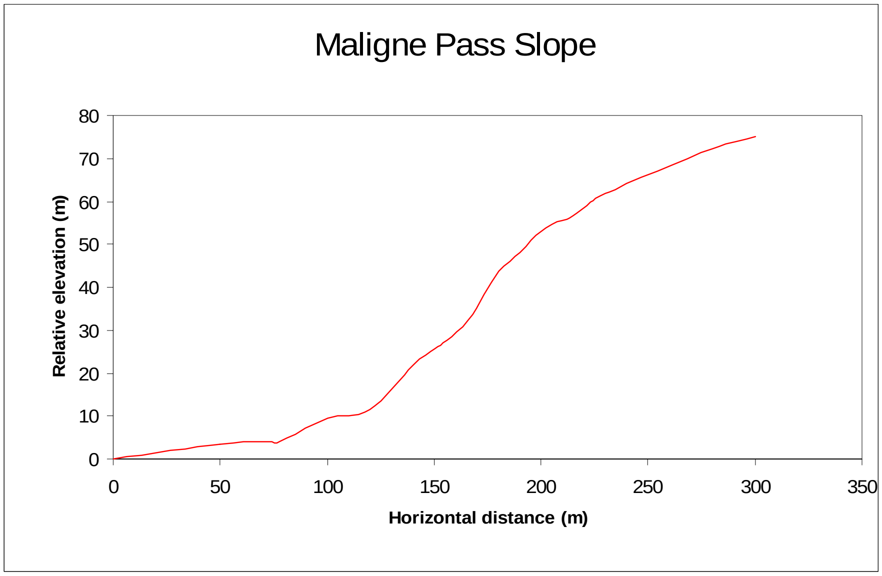

Figure 3. A reconstruction of the sampled slope at Maligne Pass, JNP

Repeat Aerial Photographs

The repeat aerial photographs did not allow for a successful comparison of the study site over time. The photos were taken at very high elevation and therefore did not permit to observe the details of small regions such as the study site. The different photographs (1949 and 1993) are shown in Figures 4 and 5.

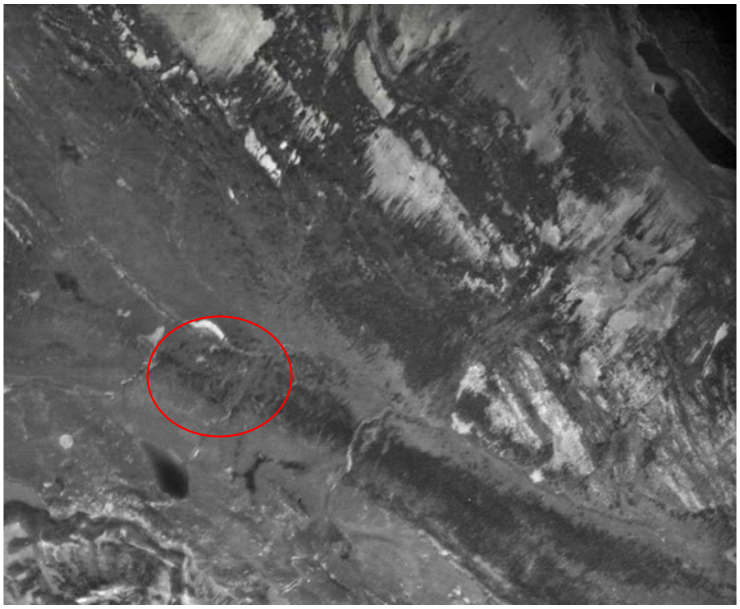

Figure 4 An Aerial photograph of the Maligne Pass area taken in 1949 (National Air Photo Library). The area encircled represents the location of the study site.

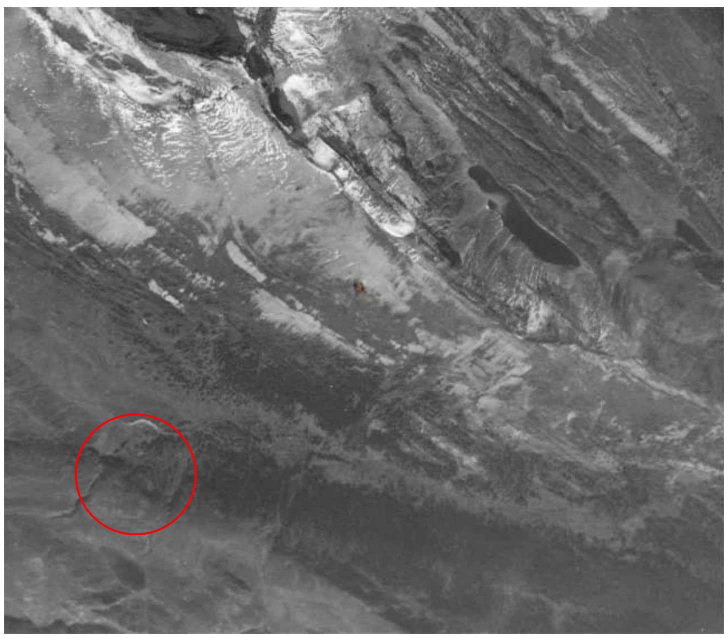

Figure 5 An Aerial photograph of the Maligne Pass area taken in 1993 (National Air Photo Library). The area encircled represents the location of the study site.

Sample Analysis

(i) Age Distribution

The core and the disk samples were used in a regression analysis to create a mathematical relationship that would allow us to determine the age of all other trees in the study site. The regression created using the diameter measurements as an indicator of age had an R^2 value of 0.524 (See Figure 6). On the other hand, the regression relating tree height and age had an R^2 value of 0.7176 (see Figure 7). This suggests that there is a higher correlation between tree height and age than between tree diameter and age. For this reason, the mathematical relationship relating height to age was used to approximate the age of the remaining undated trees.

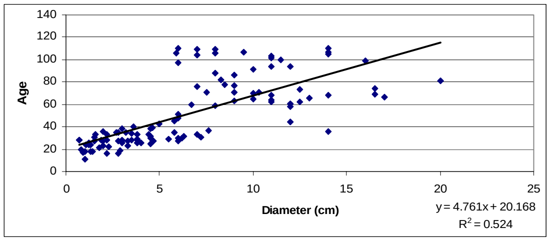

Figure 6 A graphical representation of the relationship between diameter and age for subalpine fir.

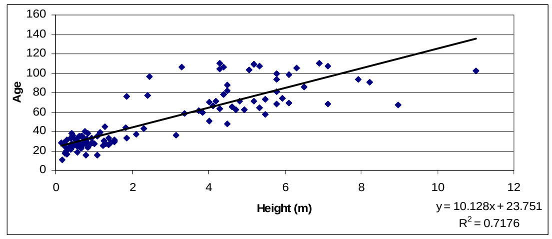

Figure 7 A graphical representation of the Relationship between height and age for subalpine fir.

The overall age distribution is shown in Figure 8 and 9. Figure 8 shows the tree ages while Figure 9 shows the establishment dates.

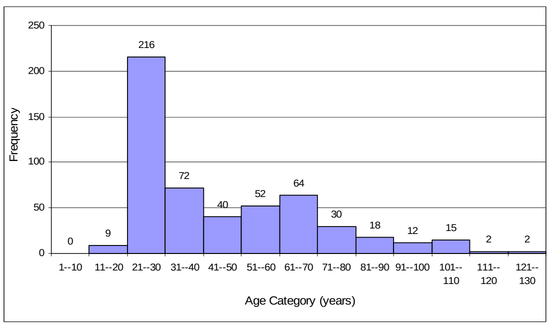

Figure 8 Age distribution of subalpine fir in Maligne Pass.

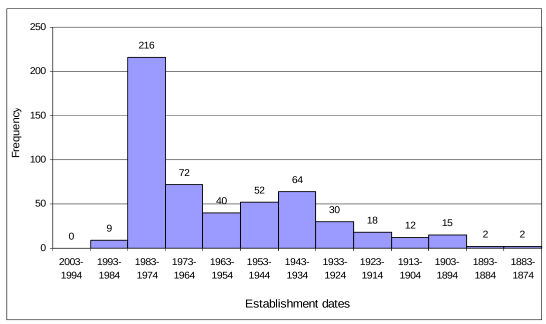

Figure 9 Establishment dates of subalpine fir in Maligne Pass.

As highlighted in Figures 8 and 9, most trees are between the ages of 21 and 30 years. The most important period of establishment occurred between 1974 and 1983. This time period corresponds to a significant growth pulse as 40% of all trees established over the course of that particular decade. Also observed on these graphs is a break in the smooth distribution curve caused by the low number of trees aged between 41 and 50 years. This would indicate a period where tree establishment was particularly low (between 1954 and 1963). Another less obvious feature illustrated by the age distribution is a small growth pulse occurring between 1934 and 1943.

(ii) Master Chronology

The overall correlation obtained with COFECHA for the samples from Maligne Pass was 0.520. This involved eliminating 15 of the 52 samples that were not showing the same growth signal as the group.

The UVTRL data set had a correlation of 0.530. A comparison of the Maligne Pass data set to the UVTRL archive data set using a Pearson's Product-Moment correlation revealed that the two study sites were comparable. The calculated r-value was 0.244 ($p<0.02$, $n=100$). The overall correlation of the pooled data sets was 0.417 (Table 2). The amalgamation of the two sample sets (04ABL300 and 99Y300) created a chronology of 49 trees with a ring pattern extending to 1640.

Table 2 A Cofecha comparison of Maligne Pass subalpine fir to Hilda Rock Glacier subalpine fir (from UVTRL archive, 1999).

Site	Time period	Number of cores (trees)	Intra-site correlation	Between site correlation
99y300 (UVTRL)	1640-1999	19 cores (12 trees)	0.530	0.417
04ABL300 (MAD Lab)	1882-2004	37 cores (37 trees)	0.520	

The resulting master chronology seen in Figure 10 illustrates the overall growth trend of subalpine fir from 1640 to 2004. Figure 11 focuses on the temporal establishment range relevant to the study site (1880-2003). The late 1600's were characterized by poor growth while the early 1700's saw good growth. The growth remained stable from mid-1700 to present. Although we see year to year variations in growth, a closer look at the past 120 years also indicates relatively stable growth. No significant increase or decrease in subalpine fir growth has been observed in this time frame.

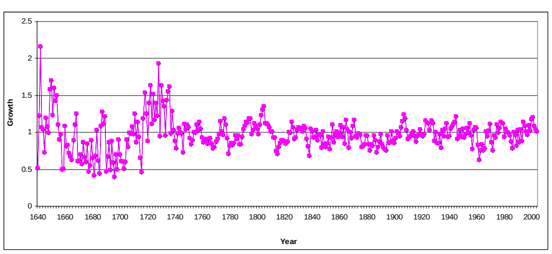

Figure 10 Master chronology of subalpine fir showing annual growth. The scale shows average growth as having the value one.

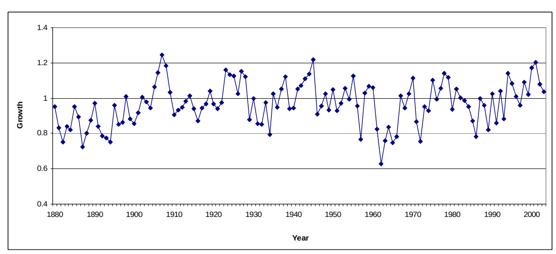

Figure 11 A close up of the growth trend for subalpine fir from 1880 to 2003.

Local Climate Data

A comparison of summer temperature records (temperature of the growing season: June, July and August) is shown in Figure 12. The Banff site shows the lowest temperatures of all three stations. This is believed to be a closer representative of the high elevation temperatures in Maligne Pass. The elevation of the study site ranged from 2160 to 2235m and Banff represents the highest elevation station at 1389m. A comparison of annual precipitation levels was also done for three different stations (Figure 13). It reveals that Banff sees mid-levels of precipitation as opposed to the low precipitation levels in Jasper and the high precipitation levels seen at the Rocky Mountain House. For this reason, the Banff precipitation data were also though to be most appropriate for this study.

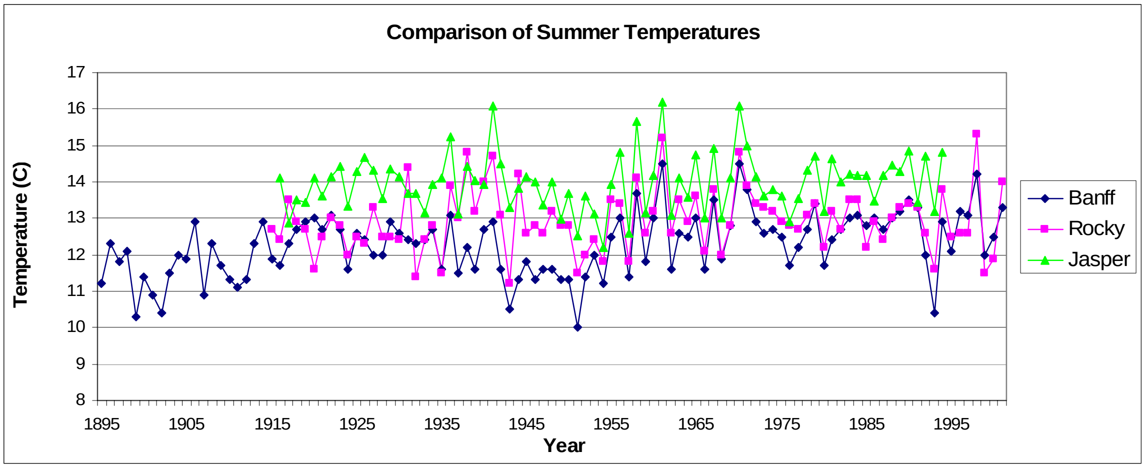

Figure 12 A comparison of growing season temperatures for three climate stations near the Maligne Pass study site. Temperature records were obtained from Environment Canada for Banff, Rocky Mountain House and Jasper.

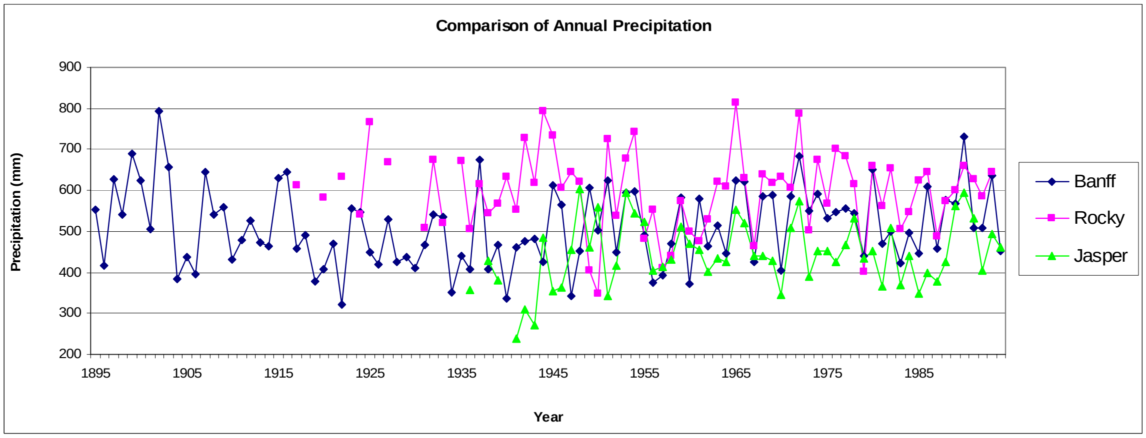

Figure 13 A comparison of growing annual precipitation levels for three climate stations near the Maligne Pass study site. Precipitation records were obtained from Environment Canada for Banff, Rocky Mountain House and Jasper.

The climate data from Banff were used to produce a relationship with the pattern of annual ring growth. Although there are many climate stations near Jasper National Park (Table 1), the Banff site was chosen because the data were readily available and also provided the most extensive record (from 1895). The Banff data was homogenised data whereas such data from Jasper was not readily available. Because of the high elevation location of the study site, the Banff climate records were believed to represent most accurately the conditions in Maligne Pass.

Growth-Climate Relationship

A principle component analysis identified the factors that significantly affect growth. Climate parameters from the Banff instrumental climate records were tested in this analysis (current and previous year's records). In addition, growth data from previous years were examined. One, two and three year lags were tested. The results of the analysis indicated that July temperature as well as the previous year's growth significantly affected growth (Figure 14). Climate accounted for 29% of the variation in growth while the previous year's growth accounted for 22.2%. The total explained variability due to these parameters was 51.2%. Precipitation levels however did not show a significant effect on tree growth variability.

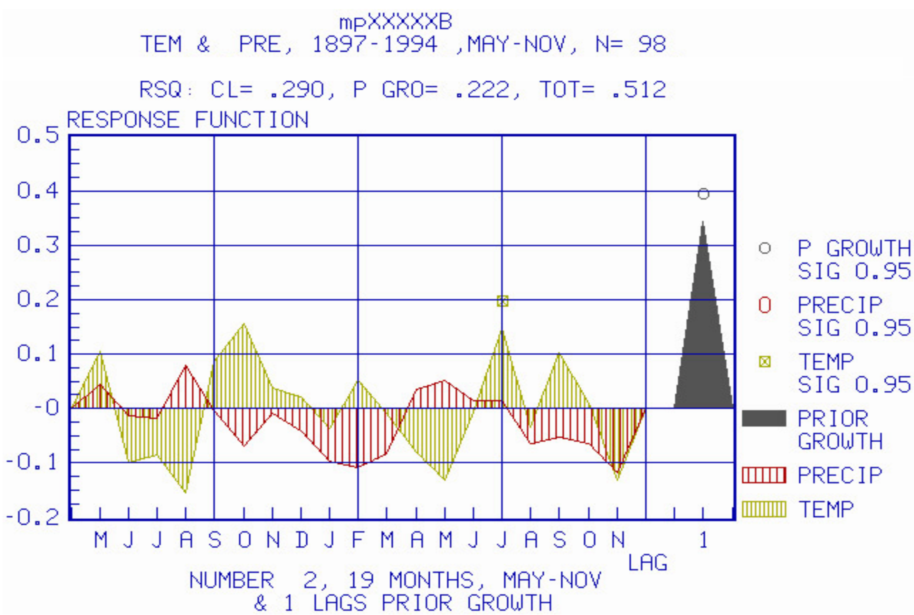

Figure 14 Result of the principle component analysis by PRECON indicating parameters significantly affecting growth variability in subalpine fir.

Future Climate and Growth

(i) Future Climate

The annual future climate data for a 3.75°x 3.75° grid cell was generated from the CGCM2. The model's results are shown in Figures 15 and 16. These data were converted to annual values; however, they were originally in monthly format.

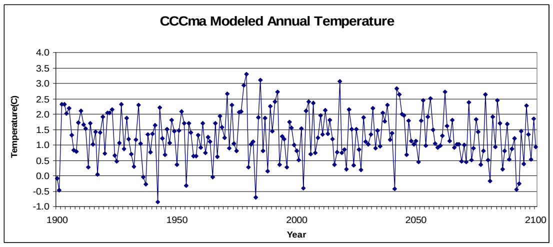

Figure 15 Annual temperature record from 1900 to 2100 generated by the CGCM2 from the CCCma

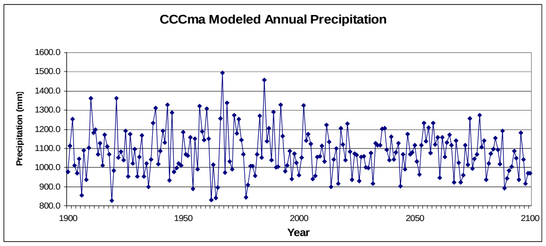

Figure 16 Annual Precipitation record from 1900 to 2100 generated by the CGCM2 from the CCCma.

The data show no trends of increase or decrease for both annual precipitation and temperature over the next century.

(ii) Future Growth

The climate data from the CGCM2 (1900 to 2000) was used in a forward step-wise multiple regression (SPSS 10.0) to generate a model of past growth for Subalpine fir. This was a means of testing if the data could accurately model the known growth pattern of subalpine fir. Figure 17 shows a comparison between modeled and actual past radial growth.

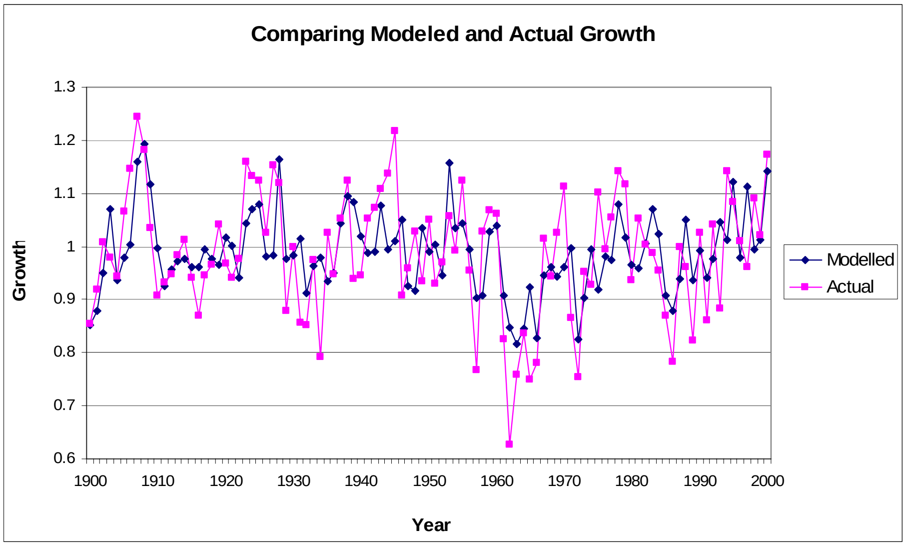

Figure 17 A comparison of actual subalpine fir growth and modeled growth generated using the CGCM2 data.

The model was able to successfully recreate the SAF growth trend; growth peaks and dips seem to coincide in time. The regression model had an R^2 value of 0.418, indicating that it is accounting for 41.8% of variability in tree radial growth.

Future growth was then modeled using the same approach, but this time using the CGCM2 1900-2100 data. The results (Figure 18) show no clear increase or decrease in SAF growth. It seems to remain relatively stable over the next 100 years.

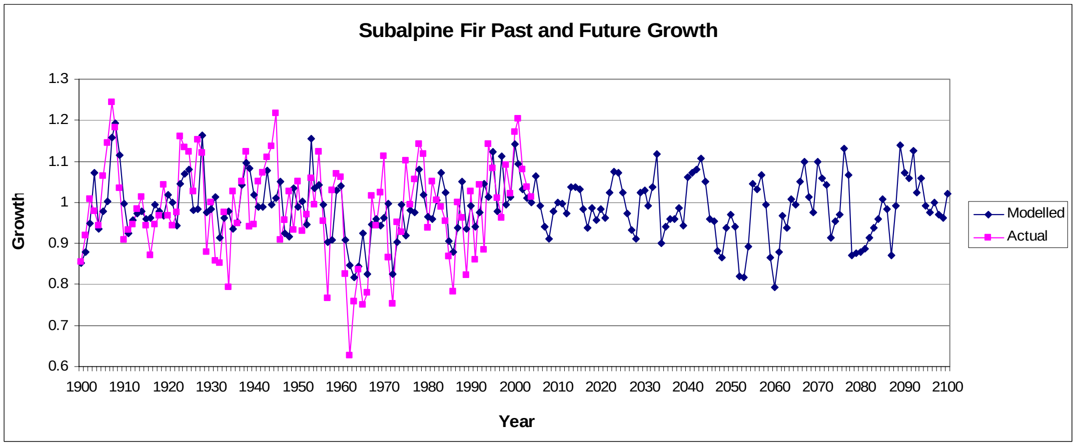

Figure 18 A graph showing the anticipated growth trend of subalpine fir until the year 2100 based on the climate data from the CGCM2.

Discussion

Field Mapping and Slope Analysis

The tree distribution at Maligne Pass reveals a density pattern that relates to the slope incline. The area of lower density seen between 165 and 180m (Figure 2 and 3) coincides with the steepest region; it is characterized by an incline of 40°. Steep inclines generally make it difficult for trees to be able to grow (Arno and Hammerly, 1985) which explains the lower density observed at mid-slope. The upper section of the study plot sees lower densities because of elevation; the conditions become too cold for SAF to survive and results in the upper tree limit. The lower tree densities observed at the bottom of the transect are explained by the cooler conditions that are characteristic of low lying areas. The valley bottom between the mountain ridges acts as a cold air sink for the region (Arno and Hammerly, 1985). Cold air drains into this pocket while the warmer air rises. This phenomenon explains the presence of the lower tree limit, which is typical of most mountain passes. The trend of establishment then began with tree clusters near the mid slope, where the oldest trees were found, followed by both up and down migration of the treeline.

Aerial Photographs

As already mentioned, the aerial photographs did not allow for a landscape comparison over time. The photographs would have needed to be taken at a lower altitude in order to decipher the landscape details of the specific study site. Because this study focussed on a very small area (3000m^2), repeat aerial photography did not prove to be a useful tool. This particular method would be most applicable to large scale landscape studies such as the one conducted by Rhemtulla *et al.* (2002).

Sample Analysis

(i) Age Distribution

The linear regression analysis revealed that age can be estimated more precisely by using the height parameter as a reference as opposed to the diameter.

The age distribution seems to fit the standard Type III survivorship curve. This type of survival curve is characteristic of organisms, such as forest trees, which have a high juvenile mortality followed by a period of low mortality (Barbour *et al.,* 1987). Figures 19 and 20 compare a typical tree survivorship curve to the one observed in Maligne Pass. Even if it is punctuated with growth pulses and growth declines, the general trend seems to be similar to that of the type III curve.

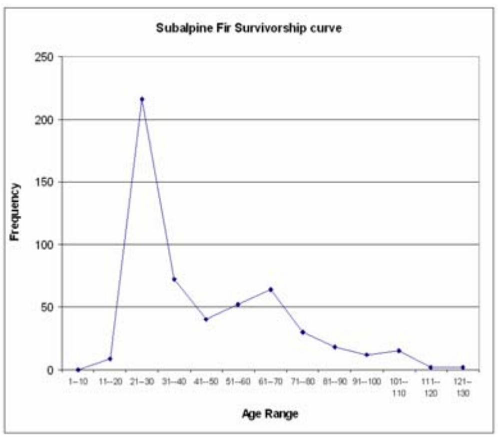

Figure 19 Survivorship curve of subalpine fir in Maligne Pass, showing a type III survivorship curve.

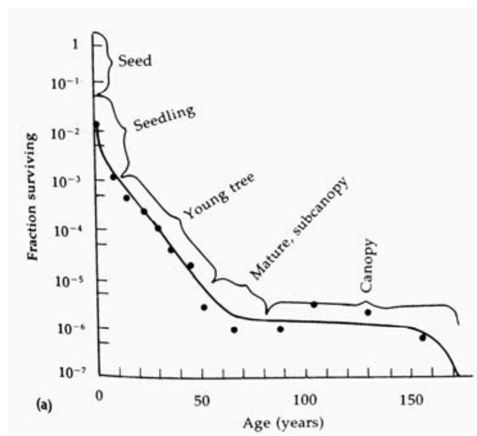

Figure 20 A typical tree survivorship curve (Barbour et al., 1987)

(ii) Master Chronology

As indicated by the master chronology, the overall growth pattern of subalpine fir from Maligne Pass was stable over the past 120 years. Although much of the past growth is characterized by year to year fluctuations that hover around the average growth value, some periods are marked with sustained above average or below average growth (Figure 21). These are periods where there was either good or bad growth for several consecutive years (6-10 years).

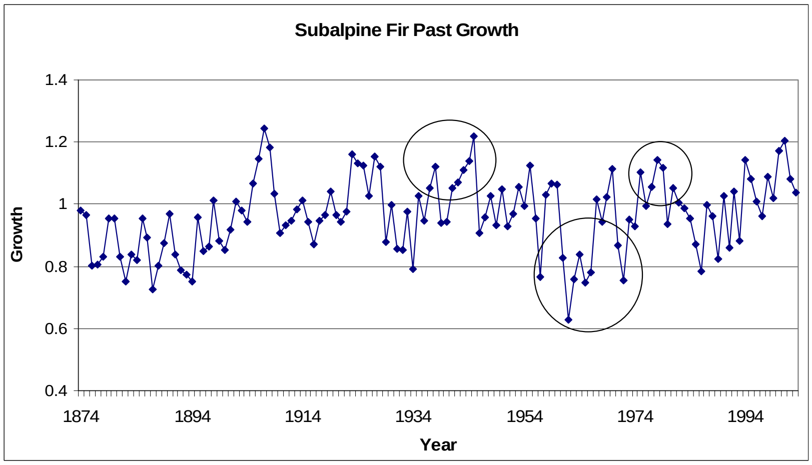

Figure 21 Master chronology of SAF showing past growth trend (1874-2004). The periods circled represent periods of either sustained above average or below average growth.

Establishment-Climate Relationship

Interestingly, if we compare the trends in establishment seen in the age distribution graph with the master chronology we can see that the growth pulses seem to correspond with periods of sustained above average growth (Figure 22). Time periods with several consecutive years of good growth seem to coincide with higher than average tree establishment. This trend is most obvious between 1974 and 1983. The large growth pulse is linked to a timeframe where there was approximately 9 years of average to above average growth. This same relation can also be found between 1934 and 1943. Again, this smaller growth pulse is concurrent with a 10 year period of good growth.

Conversely, the period with sustained below average growth seems to coincide with a decade where there was particularly low tree establishment. This can be seen from 1954 to 1963 where there is a depression in the age distribution (Figure 22).

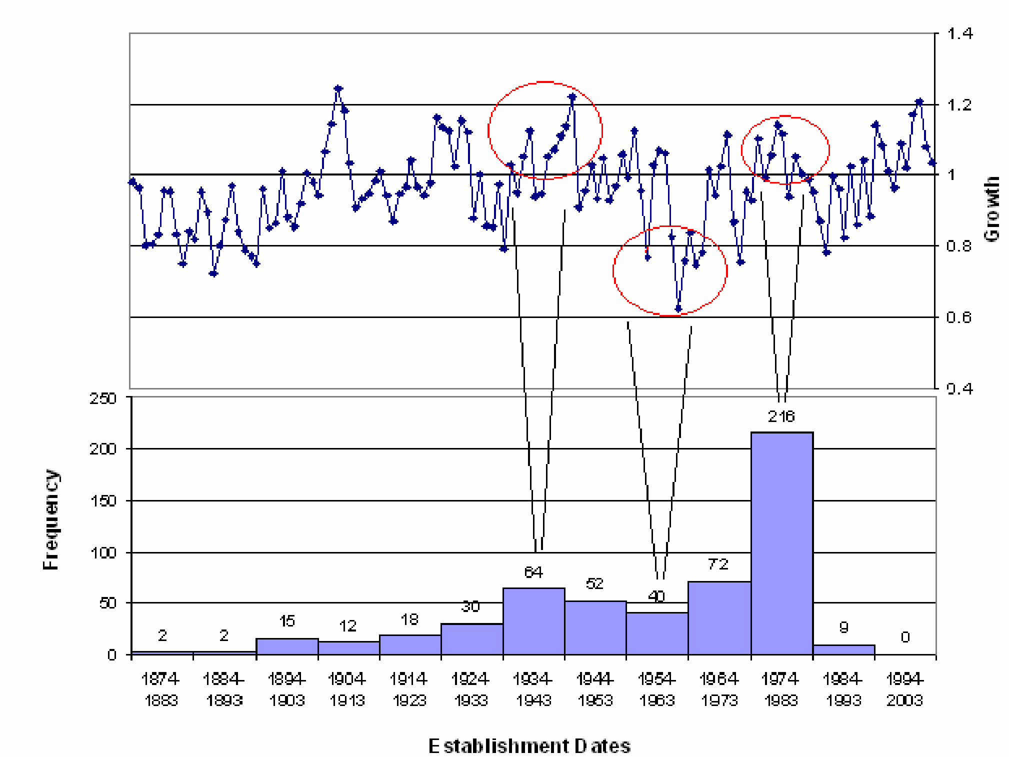

Figure 22 A graphical representation of the age distribution of subalpine fir and how it relates to the growth pattern over the last 130 years.

These results indicate that for important establishment events to occur there must be several years of good growth. We must however keep in mind that other factors also affect the rate of establishment and survival of trees. Are there then any climatic trends that coincide with these establishment periods?

The results of the principle component analysis study indicated that the climate parameter significantly affecting growth is July temperature in addition to the previous year's growth. Based on these results we hypothesised that the factors affecting growth would also affect establishment trends. We would then expect to see above average July temperatures for the periods of 1974 to 1983 and 1934 to 1943. The local instrumental climate data from Banff (Figure 23) shows a period with above average temperature between 1934 and 1943. The period extending from 1974 to 1983 had above average temperatures punctuated with cooler temperatures, which contradicted the expected results.

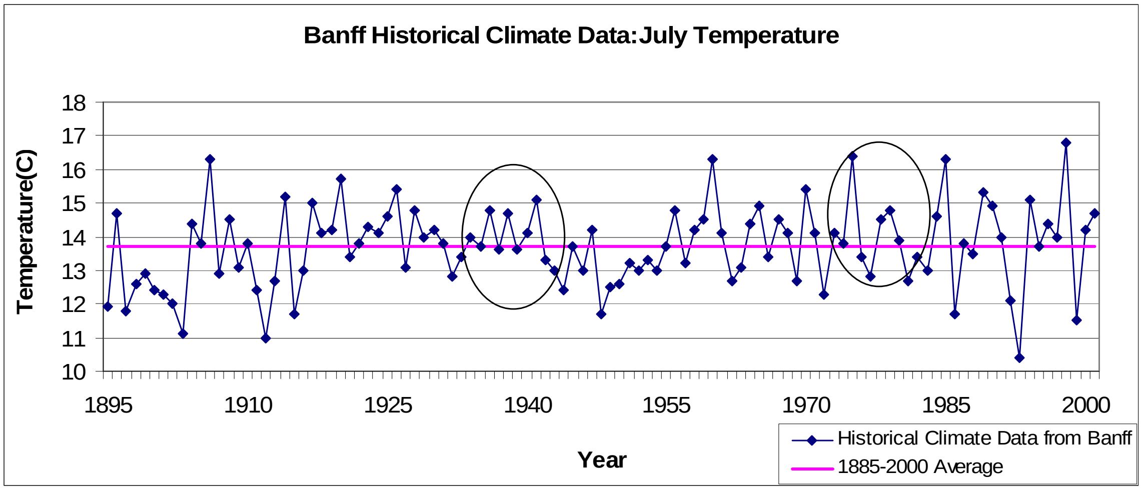

Figure 23 Historical instrumental temperature data from Banff extending from 1895 to 2000 showing the 105 year average temperature. The circled decades correspond to a period of high establishment.

Similarly, we would expect the period from 1954-1963 to show cooler temperatures as the establishment over this decade was particularly low. Figure 24 shows that this does not seem to be the case. The temperature during this period was for the most part higher than average.

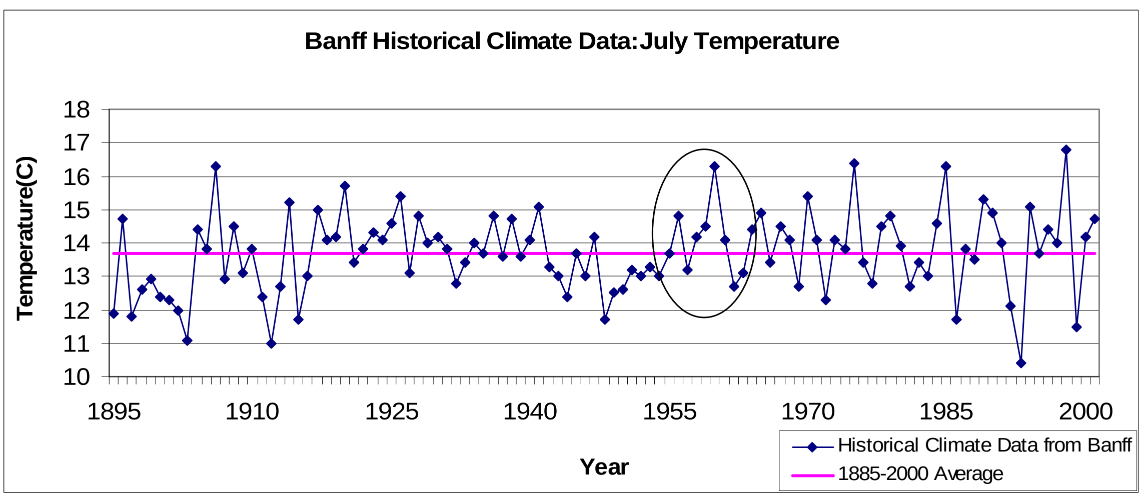

Figure 24 Historical instrumental temperature data from Banff extending from 1895 to 2000 showing the 105 year average temperature. The circled decade corresponds to a period of low establishment.

Although July temperature was found to be the only climate parameter that significantly affected growth, it alone does not seem to dictate establishment trends. Rather a complex interaction of variables must be considered in order to accurately determine establishment patterns. This reflects the results obtained with the PRECON analysis. It indicated that climate accounted for only 29% of growth variability. The remaining 71% of variability was due to other factors, including the 22.2% attributed to the previous year's growth. Establishment thus depends on a multitude of factors.

These findings differ from previous research done by Kavanagh (2000) who found significant correlations between establishment and monthly temperatures of February, June and August. In addition, she identified winter precipitation and July precipitation as significant controls on establishment. Kavanagh suggests that the length of the growing season may be a more important factor for establishment than a warmer summer in general, as the shoulder months to the growing season (June and August) were found to significantly correlate with establishment.

The failure of Kavanagh's study to identify July as a significant month affecting establishment is alarming. This is the most important month for radial growth because this growth is generally assumed to have ceased by August (Hadley and Smith, 1986). At this elevation, August is a period when carbohydrate reserves are built up for the next growing season. It is therefore reasonable to assume that July temperature reflects the growth and establishment of trees, since it encompasses the majority of the growing season.

Our study did not identify any monthly precipitation levels that significantly affected establishment. Kavanagh found that winter precipitation and July precipitation were of importance for establishment. Although winter precipitation levels are important in creating the snow pack which prevents damage from wind and ice (Arno and Hammerly, 1985), the trees remain dormant during this season. Hence, it can be argued that climate parameters become less important over this particular period. The snow pack also relates to spring moisture levels as the melted snow provides ideal conditions at the beginning of the growing season (Arno and Hammerly, 1985). Our study did not take snow pack records into consideration, which may be a parameter that affects both establishment and growth.

The inconsistencies between studies could be attributed to differences in analysis methods used. Our study used a principle component analysis while Kavanagh used a correlation analysis (identified winter precipitation as significant) and a regression analysis (identified July precipitation as significant). The principle component analysis is thought to be a more robust statistical analysis as it converts the climate parameters into independent data.

The dramatic differences between the two studies could also lie in the fact that the instrumental data used in growth and establishment analyses differed. This study used local climate data from Banff while Kavanagh used Jasper data. The Jasper data may not be very reflective of climate parameters affecting these high elevation study sites. Jasper, because of its lower elevation, sees warmer temperatures and far less winter precipitation.

Growth-Climate Relationship

The principle component analysis revealed that July temperature and the previous year's growth were the factors that significantly affected growth. The growing season in high elevation areas such as Maligne Pass is short due to harsh climatic conditions. Based on our results, we can conclude that July is the most important time for tree growth as warmer temperature during this particular month generally leads to good growth. Further, research by Hadley and Smith (1986) indicates that apical growth has usually ceased by August as the trees prepare their carbohydrate reserves for the next season. It then comes as no surprise that August temperature does not significantly affect growth. The indication that August serves as a period of nutrient accumulation explains why the previous year's growth is also very important for tree survival. A good growth year is generally an indicator of a good carbohydrate reserve and these reserves are essential in the early periods of the following growing season as the trees are dependant upon this food supply (Barbour *et al.,* 1987).

This study's findings are different from those of Kavanagh (2000), who identified current and previous mean summer temperatures, previous July precipitation and August temperature as climatic factors significantly affecting growth. As was discussed in trends in establishment, the analysis methods applied differed which can explain some of the variability between results. July should be important for tree growth as August is a period for nutrient storage. Again, the use of different climate data is also believed to be a major cause of discrepancy.

Future Climate and Growth

A closer look at the 2000 to 2100 section of the predicted subalpine fir growth (based on the CGCM2 generated data climate) reveals reoccurring trends; there are periods of sustained below average growth as well as periods of sustained above average growth. Figure 25 shows the periods where we anticipate high and low tree establishment. Low tree establishment will most likely occur between 2050 and 2060 as well as between 2080 and 2090. Conversely we expect to see a high number of trees establishing in the 2090's.

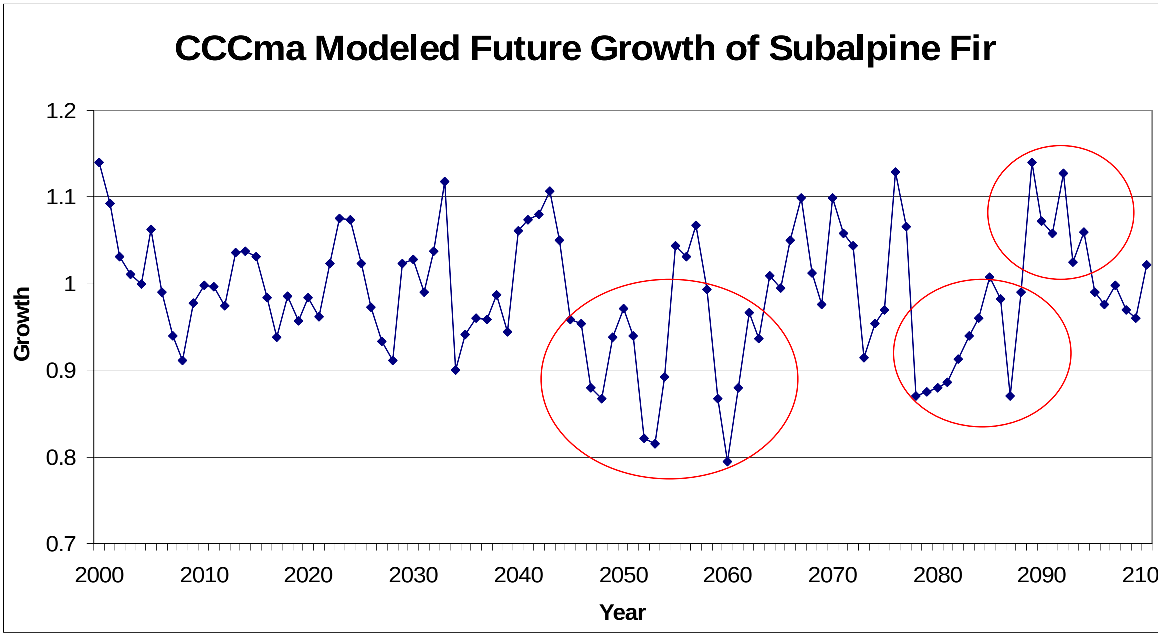

Figure 25 Future modeled growth of subalpine fir for the Maligne Pass area based on predicted climate from the CGCM2. Areas circled indicate periods of sustained above or below average growth.

The growth pattern in Maligne Pass will then continue to be characterized by growth pulses and periods of low establishment. This indicates that over the next century subalpine fir will have growth pattern that is very similar to the one that has been observed over the past 120 years.

The overall results show no dramatic increase or decrease in subalpine fir growth over the next 100 years. This is mainly due to the fact that temperature and precipitation levels are expected to remain stable. According to the principle component analysis, July temperature was most important for tree growth. The monthly climate predictions for July shown in Figure 26 fail to show any increase in temperature that could explain an increase in subalpine fir growth.

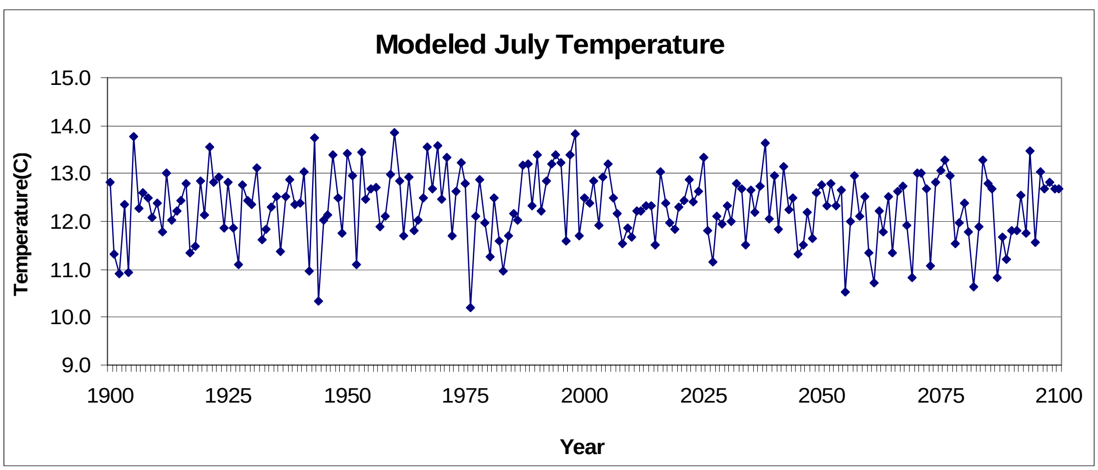

Figure 26 July temperature predictions from the CGCM2 for the period of 2000 to 2100.

Global climate change generally has a greater impact on winter temperatures (Flato et al. 2000). Because this study did not take snow pack records into consideration, there is a possibility that changes in winter temperature or precipitation levels could impact the growth of subalpine fir (*cf*. Peterson and Peterson 2001). Although the results of the PRECON analysis did not identify winter temperature or precipitation as being significant parameters affecting subalpine fir, the results of a similar study does. As already mentioned, Kavanagh (2000) found that establishment rates significantly correlated with winter precipitation as well as February temperature. These parameters could become of importance in Maligne Pass as an increase in winter temperature could mean that precipitation would fall as rain as opposed to snow. An increase in rainfall would reduce the amount of snow accumulated over the winter months, allowing for a more rapid melting of the snow pack. The rapid melting of the snow pack could be responsible for an earlier onset of tree growth, which would increase the length of the growing season. Such an occurrence could be responsible for an increase in subalpine fir growth. A decrease in winter precipitation, even with no change in temperature, could have a similar effect on tree growth as it would reduce the snow pack. Figures 27 and 28 illustrate the anticipated winter (December, January and February) temperatures and precipitation levels in the Maligne Pass.

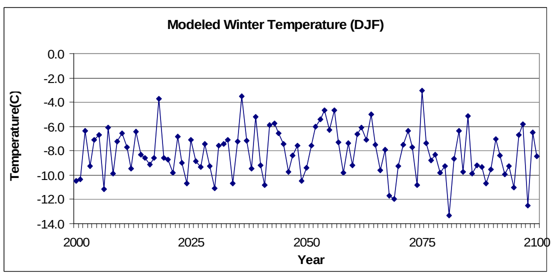

Figure 27 Winter temperature prediction by the CGCM2.

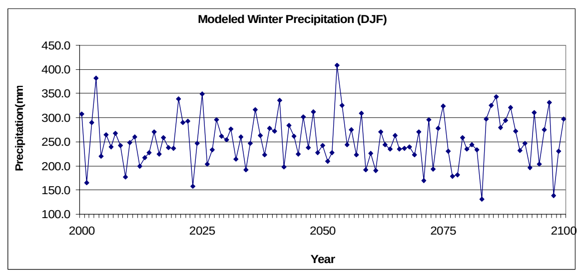

Figure 28 Winter precipitation prediction by the CGCM2.

Based on the 100 year forecast, there seems to be no major shifts in both winter temperature and precipitation. This suggests that subalpine fir will not see any strong shifts in growth pattern within this time period. The lack of a temperature increase does however seem alarming. Scientific evidence indicates that glaciers in the region have been receding for some time (Luckman 1993, 2000). Why then, is there no predicted temperature change in Maligne Pass?

This enquiry may raise questions about the validity of the CGCM2. Although this model has the ability to generate temperature and precipitation data for the entire globe, the climate data that was generated for the purposes of this project was limited to a small cell measuring 3.75˚latitude by 3.75˚longitude. This model is not disproving global climate change on the whole; rather, it is simply not predicting any changes for the Maligne Pass area grid cell (Canadian Centre for Climate Modelling and Analysis, 2005). Further, the model has been used for published scientific research throughout the world (IPCC, 2001; Kim *et al*., 2002a and 2002b). It is currently being used in the ongoing Arctic Climate Impact Assessment (ACIA, 2004) which a project that brings together scientists from Canada, Denmark, Finland, Iceland, Norway, the Russian Federation, Sweden, and the United States of America.

The CGCM2 only generated climate data from 1900 to 2100. As already mentioned, the temperature maintains a stable range over the course of this time frame (Figure 15). The model does not indicate what was occurring in the area before 1900 or what will happen after the next century. Predicting beyond 100 years can be problematic as climate models become less accurate and reliable with increased time scales and instrumental climate data ranges often limit our ability look at large-scale patterns in climate history. However, it is possible to observe reconstructed climate data based on tree ring analysis. Figure 29 shows the reconstructed climate for the study area dating from 1075 to 2000 (Luckman and Kavanagh, 2000).

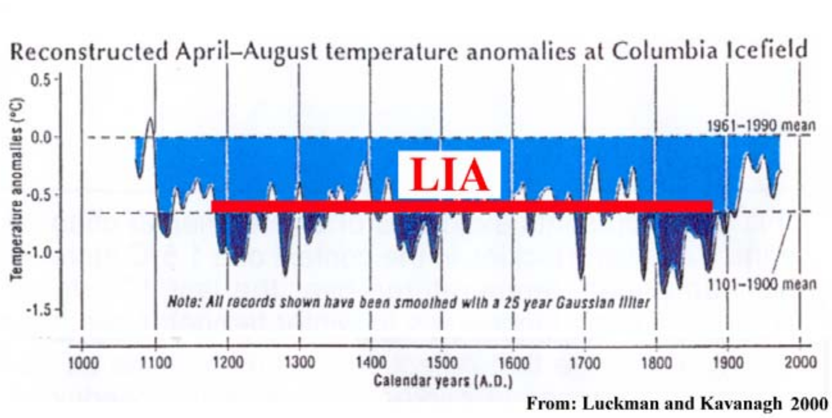

Figure 29 A reconstructed climate history of the study site area.

The data presented in this graph illustrates the Little Ice Age which saw it coldest period during the 1800's (coldest year in last 900 years occurred in 1813 [Luckman *et al*., 1997]). Subsequently, the temperature increased drastically beginning in the late 1870's and levelled off well into the 1920's. Also noteworthy is the significant difference in mean temperatures; the 1101-1900 mean is more than 0.5°C below the 1961-1990 mean. As shown in the above figure, the study site has already seen a period of warming. The CGCM2 predicted that this warmer level of temperature would continue to characterize the site over the next century.

It can then be argued that the effects of warming have already been felt at the study site. This is supported by the fact that the oldest tree on site was found to be 122 years of age; in other words there were no trees at the study site 122 years ago. A thorough investigation of the site failed to identify any coarse woody debris (CWD) which would have been an indicator of a past treeline in the area.

The establishment time frame in Maligne Pass coincides with the trend of warming that is illustrated in the climate history graph. According to the age distribution, establishment began in 1882. This corresponds to the beginning of the warming period after the Little Ice age (late 1870's). Because of this warming period, subalpine fir trees were able to establish, grow, and survive over the past 120 years. The study site was dominated by subalpine fir because climatic factors prevent other less tolerant species from surviving at the extreme elevations of the treeline. The conditions are simply too harsh for pine and engelmann spruce. These other tree species were only present at a few hundred metres down slope from the study site, where spruce forests were plentiful.

Naturally, changes in climatic conditions such as the one seen in the late 1800's caused the distribution range to expand upslope. Despite the absence of an increase in annual temperature in Maligne Pass, the growth predictions foresee that subalpine fir will continue to grow and establish in the area over the next century. The pattern of growth is expected to be similar to the one that has been observed over the past 120 years. We will continue to observe growth pulses and periods of growth decline. The patchy tree distribution which is representative of the growth pulses will continue to characterize the site. This means that the tree islands observed will persist in the area. This comes as no surprise as the tree islands are indicative of the "struggle" for existence that occurs at high elevation (Arno and Hammerly, 1985). The tree clusters develop because it enhances their chances of survival. The islands provide wind shelter, mutual mechanical support, buffering of temperature extremes, higher humidity and a black body effect that results in earlier snow melt.

The treeline is therefore not expected to advance or recede rapidly, rather; it will maintain the dynamics that have been observed in the past. The effects of climate change have already been felt in Maligne Pass and the evidence lies in the fact that there were no trees there 122 years ago. The effects may have been felt earlier or even faster as the area encompasses the upper elevation limit of the SAF distribution range.

Implications for Wildlife

The fact that the area will continue to see the patchy distribution of tree islands is of importance for certain wildlife species. The absence of an increase in tree growth indicates that the transition from tree islands to dense alpine forest will occur slowly. Open areas with scattered seedlings and saplings will persist in the area and continue to provide a source of food for small mammals (small chewed trees were common at the study site, suggesting their importance to the local wildlife).

The treeline migration observed over the past 120 years could have a positive impact on wildlife. It is creating new habitat at higher elevation, which might compensate for habitat disturbance that has been occurring in the valley bottoms due to human activity. The future changes in treeline position are predicted to occur gradually allowing for a slow process of forestation and therefore a natural process of adaptation and species migration.

Overall, no large negative impacts are anticipated for the local species of wildlife. Any changes will occur gradually, allowing the natural processes of adaptation and evolution to persist within the ecosystem.

Conclusion

The objectives of this study were to determine how the landscape in Maligne Pass has changed over the past 100 years, to determine why it has changed by relating changes to climate variations, to predict future change based on different climate change scenarios and to discuss possible implications this may have for wildlife and ecosystems.

The results indicate that Maligne Pass saw a shift in landscape over the past 100 years as the oldest tree in the study site was only 122 years old. Tree establishment began in the late1870's coinciding with the warming period that followed the Little Ice Age. Important establishment periods occurred between 1974 and 1983 as well as between 1934 and 1943. The analysis of tree distribution indicated that trees first established near the mid-slope. The upper and lower treelines were then formed and gradually migrated upslope and downslope.

Several factors were responsible for the changes in landscape of Maligne Pass. Growth of subalpine fir was found to be significantly affected by July temperature as well as the previous year's growth. Climate parameters and previous year's growth collectively accounted for 51.2% of the variability in growth. These findings were found to differ from a similar research project (Kavanagh, 2000). Differences in analysis methods as well as in local climate data utilized were most likely the main factors behind the variation in results.

The future growth predictions were based on climate projection from the CGCM2 developed by the Canadian Centre for Climate Modeling and Analysis. Temperature and precipitation levels were found to remain relatively stable over the next 100 years in the Maligne pass area, indicating that the growth of subalpine fir will also remain stable. The growth pattern is predicted to resemble the same pattern observed for this species over the past 120 years. The area will most likely continue to be characterized by scattered tree islands. As a result, no drastic shifts in treeline are anticipated.

The implications for wildlife may be positive as new habitat is being formed at higher elevation which may compensate for the habitat disturbances occurring in the valley bottoms due to human activities. This forestation process is taking place at a slow and natural pace allowing for adaptation and species migration within the ecosystem.

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