Responses of western Canadian aspen forests to climate variation and insect defoliation during the period 1950-2000

Supported in part by the Government of Canada's Climate Change Action Fund

Project A039

12 July 2001

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Summary

Trembling aspen, sometimes known locally as “white poplar”, is the most common broad-leaved tree in the Canadian boreal forest. Aspen is also the main tree found in woodlots and forest patches of the aspen parkland, a predominantly agricultural zone located along the northern edge of the Canadian prairies and in the Peace country of northwestern Alberta. Because of their abundance in western Canada, aspen forests are especially important for wildlife and recreation, and as a major supply of wood fibre for the forest industry in this region.

In the early 1990s, dieback and reduced growth of aspen was noted in some areas of Saskatchewan and Alberta. Early studies suggested that the drought, in combination with defoliation by forest tent caterpillars, played a major role. This led to concerns about the current status of aspen forest health, including the question of how aspen may be responding to the climatic warming that is already evident in western Canada.

To address these concerns, a regional study was established, entitled “Climate Change Impacts on Productivity and Health of Aspen” (CIPHA). CIPHA is a research and monitoring initiative of the Canadian Forest Service, Natural Resources Canada in collaboration with Environment Canada and other partners, with support from the Climate Change Action Fund, PERD (ENFOR), and Mistik Management Ltd.

The CIPHA study consists of a network of long-term research plots in 72 aspen stands across the boreal forest and parkland of western Canada, extending from the Northwest Territories to southern Manitoba. Tree-ring analysis has been conducted in each stand to determine how climate, insects and other factors have affected the growth and health of aspen forests over the past 50 years. Monitoring of aspen health and dieback was initiated in 2000, and is being continued to determine future changes in these forests.

Preliminary results from the tree-ring analysis show that aspen forests in western Canada have undergone several cycles of collapses in growth followed by recovery since 1950. Growth was greatly reduced during 1961-1964, 1979-1984, and 1988-1995, corresponding to periods with regional drought and large-scale outbreaks by forest tent caterpillar. The last peak in aspen growth was in 1997, following a cool, moist period with little defoliation. However, conditions were unusually dry across much of the region in 1998, which was also the warmest year ever recorded. In 2000, a severe outbreak of another insect defoliator, the large aspen tortrix, was recorded at several of the boreal sites. As a result, aspen growth dropped by 30% between 1997 and 2000, and dieback was noted in 25% of the live aspen trees. The results of continued monitoring will determine how aspen forests are responding to the impacts of the unusually warm, dry winter and spring of 2001.

Future directions of CIPHA include the expansion of the project to involve additional collaborators and stakeholders, and to use the results for the development and testing of models aimed at predicting how climate change is likely to affect the growth, health and carbon sequestration of aspen forests in the region.

Table of contents

List of tables and figures

Introduction

Trembling aspen (*Populus tremuloides* Michx.) is the most widely distributed tree species in North America, and the most abundant deciduous tree in the Canadian boreal forest. It is especially important in the western Canadian interior, both ecologically and commercially (Peterson and Peterson 1992). However, since the 1980s, dieback and reduced growth of aspen forests has been noted over some areas of the prairie provinces, especially along the southern edge of the boreal forest and in the climatically drier aspen parkland (Hogg and Hurdle 1995). Aspen decline has been raised as a public concern in northwestern Alberta (Hogg et al. submitted) and has become an important concern for the forest industry in western Saskatchewan. Recent studies by the Canadian Forest Service in collaboration with the forestry sector (Hogg and Schwarz 1999; Hogg 1999; Hogg et al. submitted) suggest that decline of aspen in these areas was caused by a combination of climatic factors (drought and early spring thaw-freeze events) and multiple-year defoliation by the forest tent caterpillar. This insect can severely affect large (>5 million ha) areas of aspen forests during major outbreaks (Brandt 1995).

Previous analyses have shown that drought is a critical factor controlling the boundary between forest and prairie in western Canada (Hogg 1994, 1997). Indeed, the southern boreal forest may develop a drier climate similar to that presently found in the aspen parkland, naturally consisting of stunted, unproductive groves of aspen interspersed with prairie. Thus drought stress could have a major impact, as identified by the Canadian Climate Program Board (foundation paper, submitted). Climate change could also lead to increases in extreme climatic events, notably thaw-freeze events in winter and early spring, which have been implicated as a major cause of large-scale forest dieback in regions elsewhere in North America (e.g., Auclair 1990, 1992; Cox and Malcolm 1997). Furthermore, climate change may lead to increases in forest insects and diseases. A major outbreak of forest tent caterpillar was recorded for the first time in the Northwest Territories in 1995 (Brandt et al. 1996), supporting earlier suggestions that this insect is favored by warm, dry climatic conditions (Ives 1981).

From a forest industry perspective, it is also important to recognize potential benefits of global change on future productivity of forests in some areas, particularly at higher elevations and more northerly locations. For example, aspen growth may be enhanced if spring leafout occurs earlier or if autumn leaf fall is delayed by longer frost-free periods. In addition, rising concentrations of atmospheric CO_2 could lead to a gradual increase in the rate of photosynthesis and forest growth, if other factors are not limiting.

Research results from a large international field experiment (BOREAS, Sellers et al. 1997), and a Canadian-led follow on initiative (BERMS) are improving understanding of detailed processes governing effects of weather variation on primary productivity and carbon sequestration in boreal forest ecosystems, including aspen (e.g., Chen et al. 1999, Black et al. 2000; Grant and Nalder 2000; Hogg et al. 2000). Most of the intensive research on boreal aspen forests is being conducted at the BOREAS/BERMS Old Aspen site, in Prince Albert National Park, Saskatchewan, where fluxes of CO_2, water vapour and energy have been monitored continuously in 1993-94 and from 1996-present. Additional long-term research and monitoring has been conducted at the Canadian Forest Service (CFS) research site located in the aspen parkland at

Batoche National Historic Park, which was aimed at examining aspen responses under a drought-prone climate (Hogg and Hurdle 1995; Hogg and Hurdle 1997).

Because the intensive research in BOREAS and BERMS has been focussed on only a few stands over relatively short time periods, we identified a major gap in applying this work for making longer-term, regional-scale assessments of climate change impacts on the aspen forests of western Canada. We also identified a need to enhance the capability for detection of changes in aspen health, productivity and dieback at the regional scale, that may be linked to climate change and associated changes in insects and diseases. Such early detection could be critical for successful adaptation to changes that may now be occurring, or which may occur in future. Thus in 1999, we initiated a new collaborative study entitled “Climate Change Impacts and Productivity of Aspen in the western Canadian Interior” (CIPHA), with funding support from the Climate Change Action Fund, ENFOR, and Mistik Management Ltd.

The CIPHA study consists of a network of long-term monitoring plots in 72 aspen stands across the western Canadian interior, that are intended to form the basis for detecting, understanding, and forecasting climate change impacts in this climatically-sensitive region.

Objectives

1) To provide “early-warning” detection of climate change impacts through monitoring of growth, health and dieback of aspen forests in climatically sensitive areas in the western boreal forest and aspen parkland.

2) To conduct detailed tree-ring analysis to understand how climatic variation, insects and other factors have affected growth and dieback of aspen forests at the regional scale over the past 50 years.

3) To apply carbon-based models to predict future changes in productivity and dieback of aspen forests in the western Canadian interior under the most likely scenarios of global change.

4) To provide a research and monitoring framework aimed at linking, promoting and expanding collaborative research and regional monitoring of productivity, ecosystem functioning and carbon sequestration of aspen forests in western Canada.

Methods

During 2000, we established an "early warning" system of long-term forest health monitoring plots in the western Canadian interior, along a regional climate gradient that extends from the cold, moist boreal forest to the warmer, more drought-prone aspen parkland.

The location of the 24 study areas extends over a distance of nearly 2000 km, from northeastern British Columbia and adjacent Northwest Territories to southern Manitoba. Twelve of the study areas are located in the boreal forest and twelve are located in the aspen parkland (Figure 1). The overall structure of the study design is shown in Figure 2.

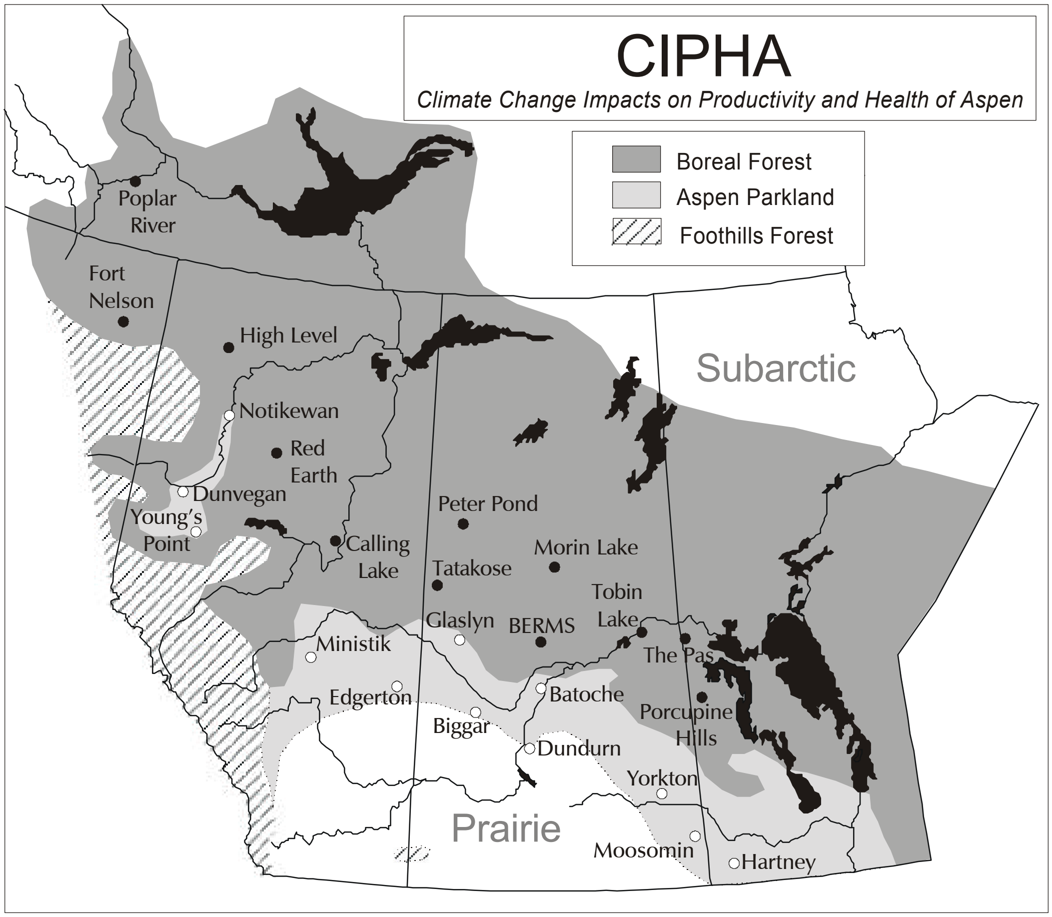


Figure 1. Map showing the location of study areas (nodes) for the CIPHA study in the western Canadian interior.

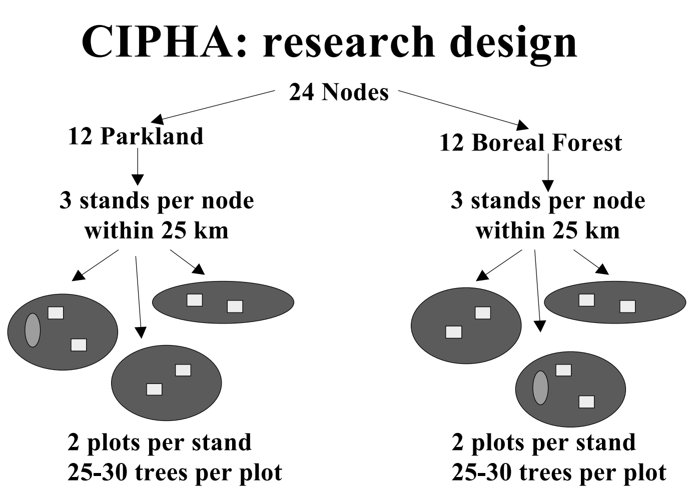


Figure 2. Diagram showing research design for the CIPHA study.

In each of the 24 study areas (nodes), three undisturbed aspen stands (40-80 years old) were selected within a distance of 25 km as a means of representing the range of dominant site characteristics in the aspen stands in that study area (total of 72 stands). Plot design was optimized for future application and validation of remote sensing methods to monitor forest responses at the regional scale. Within each stand, two permanent plots were established that were 50-100 m apart and located at least 50 m from the stand edge. Plots were rectangular with a width of 10 m. The length of each plot (typically 15-35 m) depended on stand density, and was determined as the minimum required to include at least 25 living aspen trees.

Prior to plot establishment, potential sites were scouted and potential stakeholders and land managment agencies were contacted to obtain their cooperation, permission and support. The first full year of the study (2000) included three stages: plot establishment (May-June), basic mensuration and health assessment (June-July), and stem disk collection for tree-ring analysis (August-September). Plot corners were marked using metal conduits, and their locations were recorded using a hand-held Global Positioning System unit. All standing trees in each plot were numbered and their locations within the plot were mapped, including all live and dead trees with a minimum diameter of 7 cm at 1.3-m height. Basic mensuration consisted of measurements of total height, height to top of live crown, and stem diameter (1.3-m height). Forest health assessments included visual estimates of percentage defoliation and crown dieback, incidence of forest insects and diseases with species identifications where possible, incidence of other damage (e.g., stem breakage and scarring, frost cracks, hail, and signs of external damage by woodpeckers, ungulates, bears, and other animals).

In late summer 2000, 3 aspen trees located adjacent to, but outside each plot were sampled for tree-ring analysis (total of 432 trees). Selection of trees was based on diameter classes as follows: The range of tree diameters within each plot was divided into three classes in such a way so that each class contributed equally to total plot basal area. Then at a predetermined point at least one tree height outside each plot, the nearest trees representing each of the three diameter classes was felled. Disks were collected at stump height, 1.3-m height, and at 1/3 and 2/3 of total tree height. At the 6 stands near the BERMS Old Aspen site and the CFS research site at Batoche, the same procedure was used but additional work was conducted to provide a stronger linkage between CIPHA and the process-based research at these two sites.

More intensive sampling was conducted for tree-ring analysis on the trees that were cut at Old Aspen and Batoche, where disks were collected every metre up the stems. Leaf litter fall was also collected in these 6 stands (8 bucket traps of 20 cm diameter in each of 12 plots) for monitoring changes in leaf area index, species composition of the tree and shrub layers, and leaf biomass input into the soil litter layer.

Disks were dried at 50^{o} C and prepared for tree-ring analysis by polishing with progressively finer grades of sandpaper. Tree ring widths were measured along two radii using an ocular micrometer mounted on a compound dissecting microscope at 20× magnification. Ring width measurements from the two radii were averaged and used to calculate the mean stem disk radius (R) at the end of each year's growth. Growth of each tree was expressed as annual increment in stem cross-sectional area (cm^2 y^{-1}) which was calculated from annual values of R using the formula for the area of a circle (Hogg and Schwarz 1999). Annual growth in basal area at the stand level (based on trees alive in 2000) was then calculated as follows: first, the tree-based annual area increments were expressed as a proportion of tree basal area during sampling in 2000. These annual proportions were then averaged for the 6 disks collected in each stand, and multiplied by the average live stand basal area from the two plots in that stand. The resultant values of estimated annual increment in stand basal area were expressed in units of m^2 ha^{-1} $year^{-1}$ for each year from 1950 to 2000. These results were summarized by averaging the results from the three stands within each study area (node), and then averaging of results from the 12 study areas in each vegetation zone (boreal forest and aspen parkland).

Tree rings that were abnormally pale in colour ("white" rings), indicating years when insect defoliation occurred (Hogg 1999; Hogg and Schwarz 1999), were also noted and recorded. For each year during the period 1950-2000, the overall percentage incidence of white tree rings was determined from the 18 aspen disks collected from each study area.

Analyses of climatic variation for the period 1951-2000 were conducted using daily temperature and precipitation data from long-term climate stations that were nearest to each of the 24 CIPHA study sites (Table 1). Missing data from the nearest (primary) station were estimated from one or more secondary stations after estimating the mean difference in long-term daily maximum or minimum temperature, or the mean ratio of long-term precipitation, between the primary and secondary station for those periods when both stations were reporting. The mean temperature differences or precipitation ratios were determined for each of the 12 months, and then applied as a correction to the daily data from the secondary station to provide an estimate for the primary station. In a few instances (short period of record), the precipitation ratios were based the total for all 12 months. For periods when climate data were not available for stations within 50 km, climate data was estimated from two more distant stations located in opposite directions from the study area.

The daily datasets of temperature and precipitation for each study area were used to determine annual values of the Climate Moisture Index (CMI) developed by Hogg (1997). The CMI was based on the quantity P minus PET, where P is the annual precipitation and PET is the annual potential evapotranspiration (i.e., expected loss of water vapor loss from the landscape under well-watered conditions) using a simplified form of the Penman-Monteith equation. Negative values of the CMI denote dry conditions typical of aspen parkland or prairie grasslands, whereas positive values indicate levels of moisture that are normally associated with the boreal forest (Hogg 1994). Monthly values of PET were calculated from the estimated vapor pressure deficit, which was in turn estimated from the average daily maximum and minimum temperature for each month. Precipitation and moisture conditions late in a calendar year (September-December) were assumed to have a negligible effect on the ring width for that year because radial growth of aspen is normally completed by August. Thus values of annual precipitation and the CMI were calculated for the period starting on 1 September of the previous year and ending on 31 August of the current year, which is relevant to the assessment of aspen growth responses to changes in climatic moisture regimes (Hogg and Schwarz 1999). Thermal conditions for radial growth were assessed by calculating the annual sum of growing degree days for the period ending 31 August, based on positive departures of daily mean temperatures from a base of 5°C.

Table 1. Environment Canada climate stations used to estimate daily maximum temperature and precipitation at CIPHA study sites for the period 1950-2000.

CIPHA site name	Climate station name primary	Climate station name secondary
Boreal sites:		
Poplar River, NT	Fort Simpson	
Fort Nelson, BC	Fort Nelson	Keg River
High Level, AB	High Level	Fort Vermilion
Red Earth, AB	Red Earth	Peace River, Ft McMurray
Calling Lake, AB	Calling Lake RS	Athabasca, Meanook
Peter Pond Lake, SK	Buffalo Narrows	Ft McMurray, La Ronge
Tatakose, SK	Cold Lake	Loon Lake
Morin Lake, SK	La Ronge	Whitesand Dam
BERMS Old Aspen, SK	Waskesui Lake	Prince Albert
Tobin Lake, SK	Nipawin	Choiceland, Aylsham
The Pas, MB	The Pas A	The Pas
Porcupine Hills, MB	Swan River	Kamsack, The Pas
Parkland sites:		
Notikewin, AB	Notikewin	Keg River, Manning
Dunvegan, AB	Fairview	Peace River
Young's Point, AB	Valleyview RS	Grande Prairie
Ministik, AB	Edmonton MA	
Edgerton, AB	Artland	Brownfield, Coronation
Glaslyn, SK	Butte St. Pierre	St. Walburg, Turtleford
Biggar, SK	Biggar	Scott
Batoche, SK	Rosthern	Saskatoon, Prince Albert
Dundurn, SK	Dundurn	Outlook, Saskatoon
Yorkton, SK	Yorkton	Kamsack, Indian Head
Moosomin, SK	Moosomin	Carlyle, Pierson
Hartney, MB	Brandon	Pierson

Preliminary statistical analyses were conducted to examine trends in climate, as well as growth responses of aspen to climate variation and insect defoliation for the period 1951-2000. The dependent variable describing stem growth was calculated as the natural logarithm of mean annual stand area increment (*I*) for all 72 aspen stands. Autocorrelation was removed by differencing the tree-ring chronologies to produce a stationary time series, so that regression analysis could be appropriately applied for assessment of factors affecting interannual variation in aspen growth (Hogg 1999). Differencing of the $\log_e$-transformed growth variable [$\log_e(I) - \log_e(I_{-1})$] is mathematically equivalent to generating a time series of [$\log_e(I / I_{-1})$], which thus expresses the proportional change in the current year's growth (I) relative to that in the previous year (I_{-1}). Independent variables included annual values of the Climate Moisture Index and growing degree days, each calculated annually as the average of all 24 study areas. The independent variable describing insect defoliation intensity each year was determined based on the proportion of all the aspen disks (432 trees) having white rings for each year (Hogg 1999).
In the analysis, the best fitting regression equation was obtained after step-wise inclusion of independent variables with coefficients that were statistically significant at the 5% level. Delays in growth responses were also examined by testing the inclusion of each independent variable with a 1-, 2- or 3-year time lag in the regression equations.

Other types of climate information were also examined that were expected to be relevant to the growth, health and dieback of aspen forests in the region. These included extreme weather events, snow depth, hail, heavy snowfall events in spring and early summer, and the timing of soil thaw and freeze at various depths; however, these data were not available for most of the climate stations near the CIPHA study sites. Thus, we present selected analyses for climate characteristics where long-term data were available for several stations relevant to the CIPHA study region.

For trends in snow depth, we examined long-term trends for 28 February and 31 March, because the late winter snowpack not only provides moisture for subsequent aspen growth in spring, but may also protect the trees from root damage by thaw-freeze events (Cox and Malcolm 1997; Hogg et al., submitted). Within the region of interest, snow depth data were examined from 10 climate stations, but data were available for the full period of our analysis (1951-2000) at only 5 of these stations (Grande Prairie, Fort McMurray, Saskatoon, Yorkton and The Pas).

Although its effects are localized, hail can cause severe damage to aspen stands (Riley 1953) and thus its potential impacts need to be considered from a climate change perspective. The current national hail climatology based on the period of 1977-1993 (Etkin and Brun 1999) was examined to provide an indicator of spatial variation in hail damage risk to aspen forests across the CIPHA study region. The more detailed spatial analysis was made possible through changes in observing policy within Environment Canada in 1977, which required that all weather stations report days with hail (previously only first-order climate stations were required to report hail events).

Results and discussion

Characteristics of aspen stands in the boreal forest and parkland zones

The aspen stands included in the CIPHA study had an average age of about 60 years in each of the boreal and parkland sites, based on tree-ring analysis of basal disks (Table 2). Stands ranged in age from 41 to 81 years, with the oldest stand being the BERMS Old Aspen site, which originated from fire in 1919. Although average stem diameter (1.3-m height) was very similar between the boreal and parkland sites, average tree height and stand basal area were substantially smaller in the parkland.

High variation was noted among the sites in terms of the percentage of dead aspen and the estimated percentage crown dieback (live aspen only). Despite its age, the BERMS Old Aspen site was one of CIPHA sites least affected by crown dieback. In contrast, the sites with the greatest incidence of crown dieback were relatively younger stands (High Level and Young's Point, both located in northwestern Alberta). Although statistical analyses have not yet been conducted, there was an overall trend for the parkland sites to exhibit greater percentage incidences of dead aspen and crown dieback compared to the boreal sites.

Incidence of white tree rings indicating past insect defoliation

During the tree-ring analysis, white tree rings were recorded in the disks from all but one (Moosomin) of the CIPHA sites. Previous studies (Hogg 1999, Hogg and Schwarz 1999, Hogg et al. submitted) indicate that these white rings are formed during years with severe defoliation by forest tent caterpillar and other insects. High variation among sites was noted in the average number of white rings per tree, with only a slight tendency for more white rings at the parkland sites (2.6) compared to the boreal sites (2.2). At both the parkland and boreal sites, the greatest percentage incidence of white rings were recorded for1962-1964 and during many of the years from 1979-1995. These periods correspond to major, regional-scale outbreaks of the forest tent caterpillar that were recorded during annual insect surveys by the Canadian Forest Service, especially 1962-1963, 1979-1982 and 1988-1989.

Tree-ring analysis of past variation in aspen growth for the period 1950-2000

At the regional scale, aspen showed high interannual variation in growth, based on average basal area increments in the disks from the 1.3-m height (Figure 4). In both the boreal and parkland sites, there were several cycles of reduced growth followed by growth recovery. The most notable collapse in growth occurred between 1976 and 1980-1981, when average stand area increment decreased by about 50%. A preliminary examination of Figures 3 and 4 shows that the periods of reduced growth were generally associated with major insect defoliation events in the region. The tree-ring analysis also indicates that the most recent peak in aspen growth occurred during 1997, and that growth decreased substantially during 1997-2000, especially in the boreal sites (growth reduction of 34%).

Table 2. Summary of stand characteristics for CIPHA study sites. Averages are based on three aspen stands per study site.

	Age in 2000 (years)	Basal area (m^2/ha)	Average dbh (cm)	Average height (m)	% dead	% crown dieback*	Average white rings**
Average of boreal sites:	60.5	31.8	16.1	19.0	15.8	20.5	2.2
Average of parkland sites:	60.3	26.2	16.1	14.8	18.7	31.1	2.6
Boreal sites:							
Poplar River, NT	57	33	13	18	17	25	0.4
Fort Nelson, BC	49	31	12	18	4	35	0.7
High Level, AB	58	28	13	18	20	54	2.8
Red Earth, AB	52	37	15	20	20	9	1.0
Calling Lake, AB	50	30	14	17	14	16	2.1
Peter Pond Lake, SK	59	32	17	21	17	21	3.7
Tatakose, SK	58	30	14	17	21	15	4.1
Morin Lake, SK	70	23	14	15	14	22	3.1
BERMS Old Aspen, SK	81	34	22	21	18	4	2.5
Tobin Lake, SK	60	43	21	25	13	15	1.9
The Pas, MB	57	27	17	19	15	9	2.3
Porcupine Hills, MB	76	34	20	20	16	20	1.2
Parkland sites:							
Notikewan, AB	65	26	16	19	29	49	3.6
Dunvegan, AB	56	24	13	14	20	4	5.6
Young's Point, AB	56	29	13	16	16	57	4.0
Ministik, AB	64	25	20	17	30	37	4.3
Edgerton, AB	68	28	18	15	17	44	2.1
Glaslyn, SK	69	21	17	16	27	32	3.2
Biggar, SK	54	26	13	13	23	21	4.0
Batoche, SK	79	30	20	15	22	45	1.5
Dundurn, SK	64	28	13	11	8	22	0.3
Yorkton, SK	49	30	16	15	4	6	1.4
Moosomin, SK	41	21	12	10	15	19	0.0
Hartney, MB	61	25	21	17	17	36	1.4

*Percentage of live trees with crown dieback >10%
**Average total number of white rings per tree for the period 1950-2000

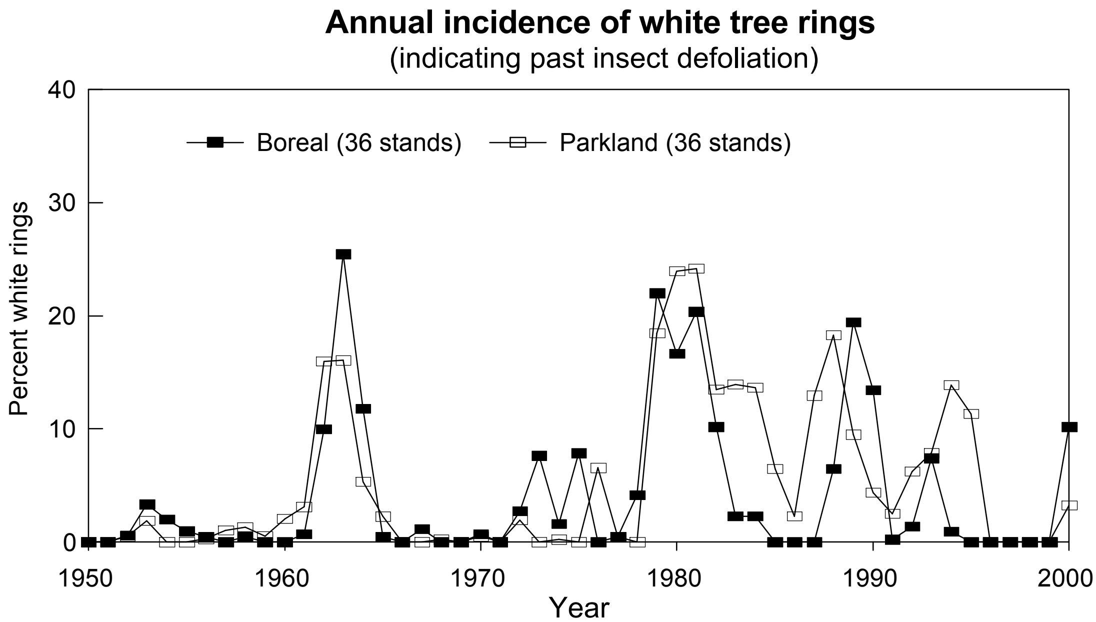


Figure 3. Average annual percentage incidence of white tree rings in aspen disks collected from 36 aspen stands (216 trees) in each of the boreal and parkland sites, for the period 1950-2000. White tree rings indicate defoliation by forest tent caterpillar and other insects.

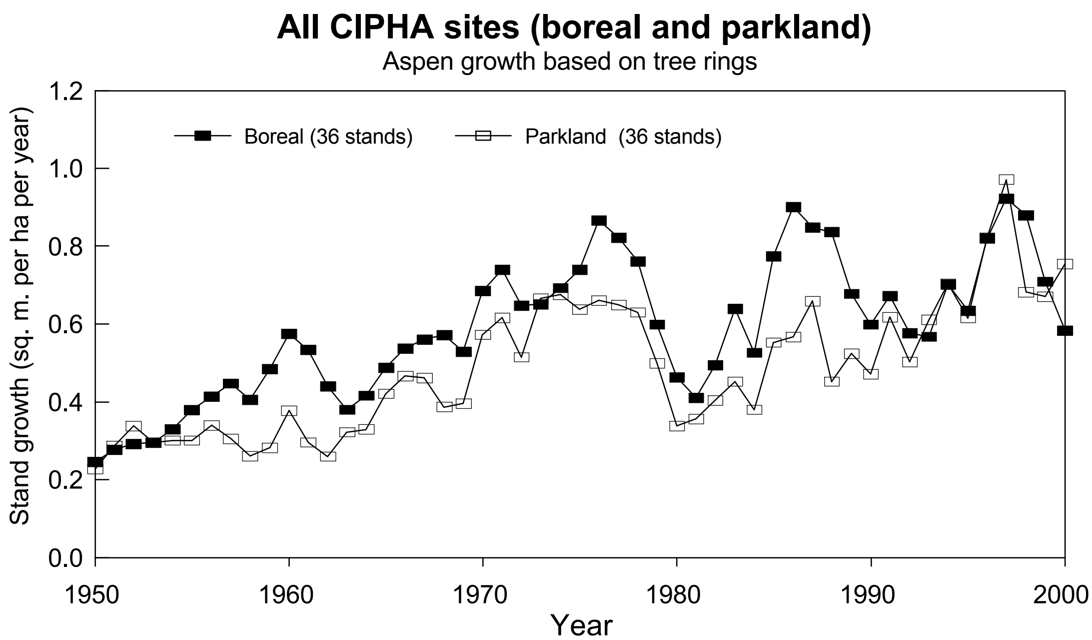


Figure 4. Estimated annual stand growth at CIPHA sites in the boreal forest and parkland during 1950-2000, based on tree-ring analysis of disks collected from 432 aspen stems. Stand growth is based only on aspen trees that were living in the year 2000.

Incidence of damage recorded during health assessments in 2000

Results of forest health assessments at the CIPHA sites during 2000 indicated that aspen forests in the region were affected by a wide variety of damage agents (Tables 3 and 4). The major categories of damage agents included woody diseases (cankers, conks, galls and rot produced by fungal pathogens), woody insects (primarily poplar borers), mechanical damage (e.g., stem breakage and scarring induced by falling trees and stem interaction), as well as damage by weather (hail and frost cracks) or by birds and mammals (e.g., woodpeckers, moose and bear). The two CIPHA sites with evidence of severe hail damage (Dunvegan and Glaslyn) were both located in the parkland zone (Table 3). The overall average incidence of total damage agents recorded per tree was nearly twice as great at the parkland sites (1.13) compared to the boreal sites (0.59), although this difference has not yet been tested for its statistical significance.

Insect defoliation during forest health assessments in 2000

Large aspen tortrix was recorded at 8 of the 24 CIPHA study sites during 2000. The three sites showing moderate to severe defoliation by this insect were located in northwestern Alberta (High Level and Young's point) and adjacent British Columbia (Fort Nelson). White tree-rings were recorded for the year 2000 in the disks collected from these three sites (11 out of 18 disks with white rings at High Level and Fort Nelson where defoliation was severe; and 7 out of 18 disks at Young's Point where defoliation was moderate). None of the year 2000 tree-rings were white at any of the other CIPHA sites (trace to light defoliation). These observations support earlier studies showing that white tree-rings provide a useful indicator of past insect defoliation events at the tree and stand level (Hogg and Schwarz 1999, Hogg 1999, Hogg et al. submitted).

Climate of the CIPHA study region during 1951-2000

The pattern of regional variation in moisture and growing season warmth during the latter half of the 20th century was generally similar in the boreal forest and parkland sites, based on the annual values of the Climate Moisture Index and growing degree days (Figure 5). As expected, the average growing degree days was greater in the parkland (1222) than in the boreal forest (1143), whereas the average Climate Moisture Index showed drier conditions in the parkland (-6.7) than in the boreal forest (+1.7). Major drought years were recorded in 1958, 1961, 1967, 1980-81, and 1998 in both zones, whereas the 1988 drought primarily affected the parkland sites. The most severe regional drought was in 1961, which was also warmer than average based on the number of growing degree days. According to Zoltai et al. (1991), this drought led to severe mortality of aspen groves over large areas of the parkland in southern Saskatchewan and Manitoba.

The warmest year ever recorded was 1998, both globally and nationally. For Canada as a whole, mean temperatures in 1998 were +2.5°C above the long-term normals, while the Northwest Territories (Mackenzie District) averaged +3.9°C above normal. In terms of total precipitation, 1998 was also the 9th driest on record (2.7% below normal precipitation) nationally, and the driest on record in the forested areas of the Prairie Provinces, northern B.C. and southern Yukon (based on the period since 1948, from the Climate Trends and Variations Bulletin for Canada

Table 3. Preliminary summary of major damage agents recorded at CIPHA sites during health surveys in 2000. Values indicate the average number of damage agents per tree for each category, or for specific damage agents, the proportion of trees affected (number of CIPHA sites affected are shown in parentheses).

	Boreal sites	Parkland sites
Woody diseases	**0.33 (12)**	**0.53 (12)**
Major agents:		
White rot (*Peniophora polygonia*)	0.17 (12)	0.02 (7)
False tinder conk (*Phellinus tremulae*)	0.05 (10)	0.13 (12)
Blind conk (conk obscured by tree growth)	0.00 (0)	0.11 (5)
Hypoxylon canker (*Entoleuca mammata*)	0.02 (5)	0.06 (8)
Diplodia gall (*Diplodia tumefaciens*)	0.01 (6)	0.05 (9)
Woody insects	**0.04 (12)**	**0.10 (12)**
Poplar borers (*Saperda* and *Agrilus*)	0.01 (3)	0.08 (12)
Other damage	**0.22 (12)**	**0.50 (12)**
Major agents:		
Breakage, scarring and whipping	0.13 (12)	0.17 (12)
Frost crack	0.06 (12)	0.14 (11)
Hail	0.00 (0)	0.07 (2)*
Animals	0.01 (6)	0.05 (9)
All damage agents:	**0.59 (12)**	**1.13 (12)**

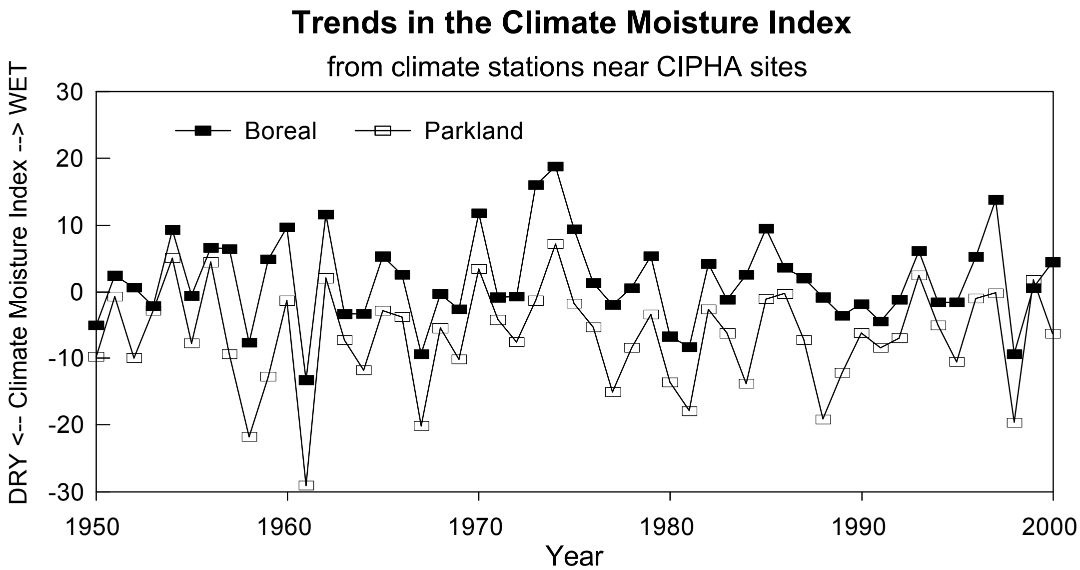
*Evidence of past damage by hail was recorded at the following CIPHA sites: Glaslyn (50% of stems affected) and Dunvegan (30% of stems affected).

Table 4. Insect defoliation and damage agents recorded at CIPHA study sites in 2000, based on three aspen stands (minimum of 75 trees) per site.

	Insect defoliation*	Major insect species**	Average number of damage agents per tree			
			Woody diseases	Woody insects	Other damage	All damage
Average of boreal sites:			0.33	0.04	0.22	0.59
Average of parkland sites:			0.53	0.10	0.50	1.13
Boreal sites:						
Poplar River, NT	moderate	ASL	0.52	0.02	0.31	0.85
Fort Nelson, BC	severe	LAT	0.44	0.01	0.12	0.57
High Level, AB	severe	LAT	0.22	0.01	0.33	0.56
Red Earth, AB	light	FTC	0.44	0.01	0.10	0.55
Calling Lake, AB	light		0.56	0.01	0.19	0.76
Peter Pond Lake, SK	trace		0.33	0.04	0.21	0.58
Tatakose, SK	trace		0.11	0.02	0.34	0.47
Morin Lake, SK	trace		0.24	0.21	0.33	0.78
BERMS Old Aspen, SK	trace		0.19	0.05	0.33	0.57
Tobin Lake, SK	light		0.07	0.01	0.19	0.27
The Pas, MB	light		0.40	0.07	0.12	0.59
Porcupine Hills, MB	trace		0.41	0.01	0.11	0.53
Parkland sites:						
Notikewin, AB	light	LAT	0.36	0.04	0.60	1.00
Dunvegan, AB	trace	FTC	0.57	0.11	0.93	1.61
Young's Point, AB	moderate	LAT	0.33	0.04	0.73	1.10
Ministik, AB	light		0.59	0.04	0.77	1.40
Edgerton, AB	light	LAT	0.47	0.05	0.67	1.19
Glaslyn, SK	trace		0.40	0.42	0.66	1.48
Biggar, SK	light		0.04	0.21	0.23	0.48
Batoche, SK	trace		0.33	0.09	0.23	0.65
Dundurn, SK	light	LAT	1.22	0.07	0.18	1.47
Yorkton, SK	light		0.34	0.05	0.20	0.59
Moosomin, SK	light	LAT	0.41	0.06	0.51	0.98
Hartney, MB	trace	LAT	1.27	0.07	0.29	1.63

*Derived from field estimates of average percentage loss of foliage in the following categories: Severe >50%, moderate 21-50%, light 10-20%, trace <10%

**LAT= Large aspen tortrix (*Choristoneura conflictana*), FTC = Forest tent caterpillar (*Malacosoma disstria*), ASL = Aspen serpentine leafminer (*Phyllocnistis populiella*)



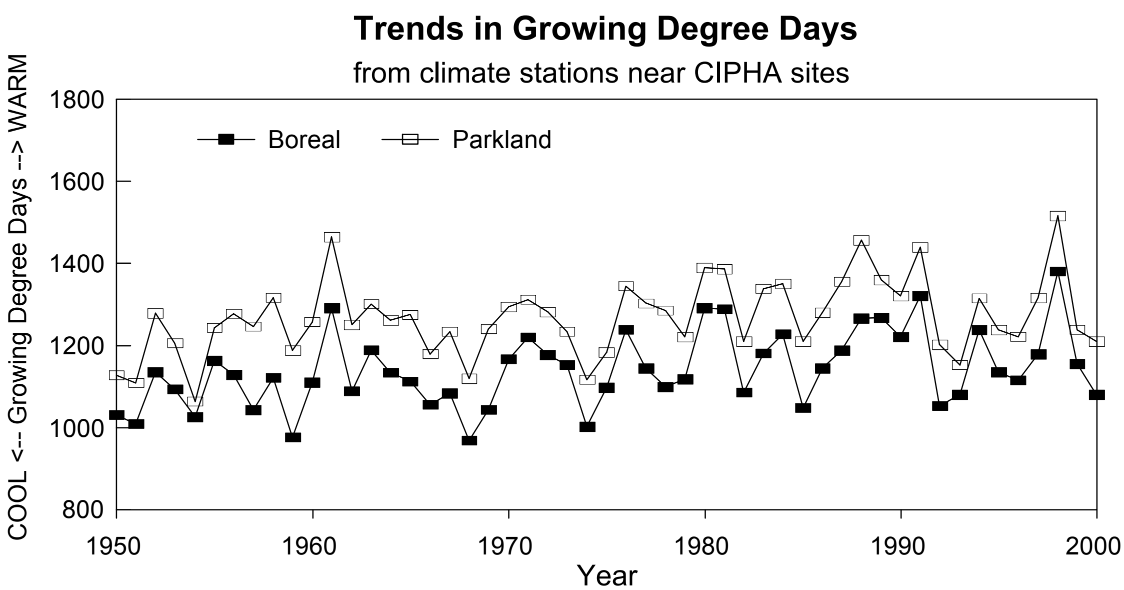


Figure 5. Trends in the Climate Moisture Index and growing degree days, based on records of daily temperature and precipitation from Environment Canada climate stations located near the 24 CIPHA study sites. Average values for the 12 boreal sites and the 12 parkland sites are shown.

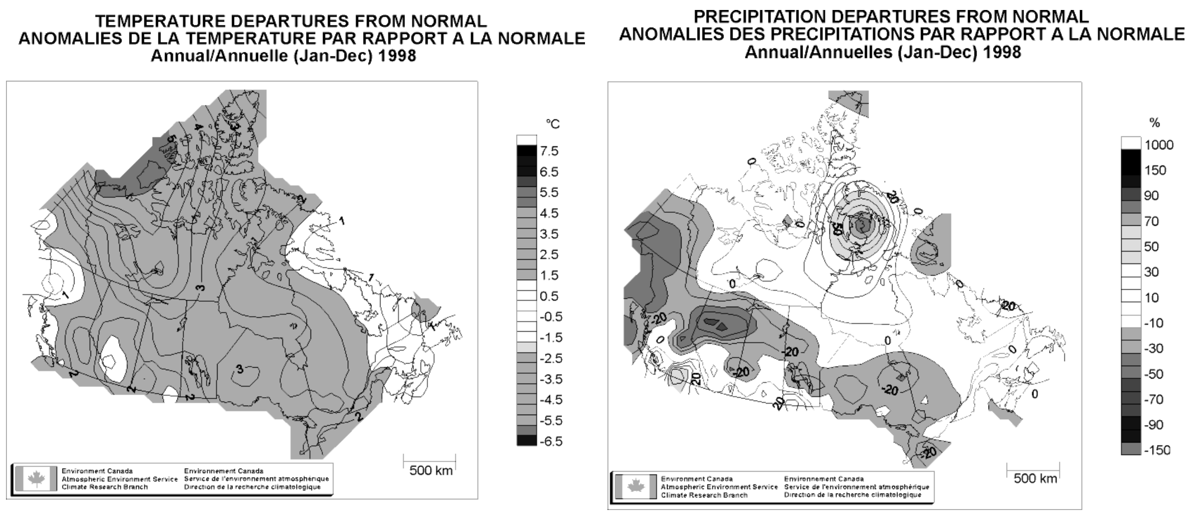


Figure 6. Departures of mean temperature and precipitation in Canada for the period January to December 1998, from the Climate Trends and Variations Bulletin for Canada web site (http://www.msc-smc.ec.gc.ca/ccrm/bulletin/archive.htm), Climate Research Branch, Meteorological Service of Canada, Environment Canada.

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web site, http://www.msc-smc.ec.gc.ca/ccrm/bulletin/archive.htm). The maps from this reference (Figure 6) show that the entire CIPHA study region was warmer and drier than average in 1998, except in the southernmost areas of Manitoba and Saskatchewan, which were slightly wetter than normal.

The climate record for stations in the CIPHA study region (Figure 5) showed that 1998 was the warmest on record overall in terms of growing degree days, and the driest overall since 1967 in terms of the Climate Moisture Index (calculated for the period 1 September 1997 to 31 August 1998). This 12-month period was the driest on record at four of the parkland sites in Alberta (Notikewin, Dunvegan, Young's Point and Edgerton) and at the two northernmost sites in Saskatchewan (Peter Pond and Morin Lake). In contrast, conditions were slightly wetter than normal during this period at three of the CIPHA sites in the southernmost areas of eastern Saskatchewan and Manitoba (Moosomin, Hartney and Porcupine Hills).

<u>Preliminary analysis of aspen growth responses to climate and insect defoliation</u>

Regression analysis was conducted on the average results for all 24 CIPHA study areas to examine the influence of climate variation and insect defoliation on regional-scale variation in aspen growth over the period 1952-2000. Growth variation was expressed as $\log_e (I / I_{-1})$, where I and I_{-1} are the average increment in stand basal area for the current and previous year, respectively. The analysis resulted in the following regression equation ($r^2 = 0.476$):

[1] $$\log_e (I / I_{-1}) = 0.060 - 0.0164\, D + 0.0133\, D_{-1} + 0.0103\, CMI ,$$

where D and D_{-1} indicate the level of insect defoliation during the current and previous year based on the incidence of white tree rings, and CMI is the Climate Moisture Index (1 September of the previous year to 31 August of the current year. Each of the regression coefficients in this equation was statistically significant, based on the respective t values of -4.55, 3.71, and 4.21 for D, D_{-1}, and CMI ($P < 0.001$ for all coefficients). Surprisingly, aspen growth showed no significant relationship with the annual number of growing degree days ($t = 0.74$, $P > 0.5$), when this variable was included in the above equation. Similar equations (not shown) were obtained when the regression analysis was conducted separately for the boreal forest and aspen parkland sites.

Thus, this preliminary analysis suggests that regional-scale variation in aspen growth has been more sensitive to variation in moisture (*CMI*) than to variation in growing season warmth (*GDD*). The results also indicate that aspen growth variation was strongly reduced by insect defoliation during the current year (D), but the positive value of the regression coefficient for the previous years' defoliation (D_{-1}) indicates that aspen growth tends to recover during the year following insect defoliation events.

Climate change trends in the CIPHA study region

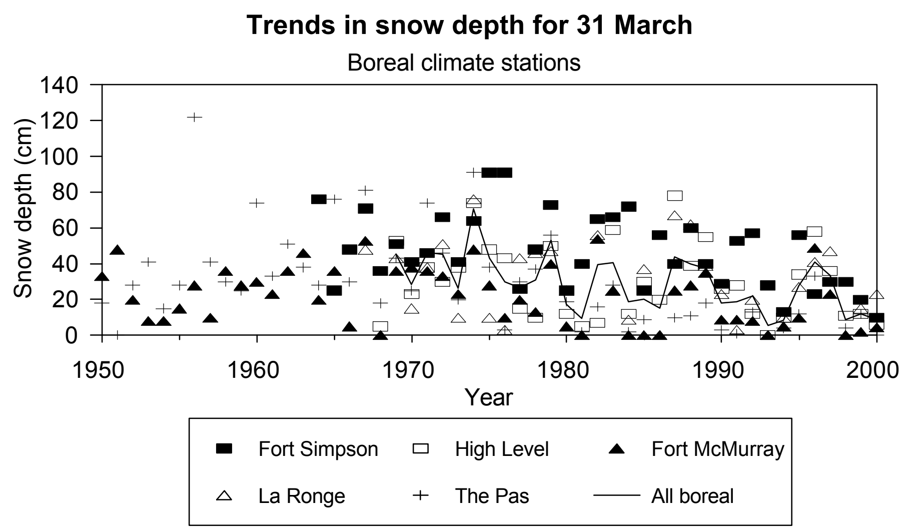
Previous analyses of the climate record have shown a significant warming of 1.0 ºC at the national scale during the period 1895-1992, with greater than average warming of 1.4-1.7 ºC in the boreal regions of the western Canadian interior (Environment Canada 1995). Precipitation has shown a slight increasing trend for Canada as a whole, but little evidence of change in the western Canadian interior.

Table 5. Trends in climate characteristics for the study area during the period 1951-2000, based on regression analysis. The variable Y indicates the number of years since 1950. Analyses are based on average climate data from stations near each of the 24 CIPHA sites, except for snow depth (average of Grande Prairie, Fort McMurray, Saskatoon, Yorkton and The Pas).

Regression equation:	Estimated change 1951-2000	Statistical significance of trend
Mean annual temperature = 0.0 + 0.034Y	+1.7ºC	P < 0.005
Mean annual daily maximum temperature = 5.9 + 0.030Y	+1.5ºC	P < 0.02
Mean annual daily minimum temperature = -6.0 + 0.039Y	+1.9ºC	P < 0.001
Growing degree days = 1151 + 2.22Y	+109	P < 0.02
Mean annual precipitation = 430 + 0.20Y	+10 mm	NS*
Climate Moisture Index = -2.1 + 0.012Y	-1	NS
Snow depth on 28 February = 41.4 - 0.45Y	-19 cm	P<0.002
Snow depth on 31 March = 30.6 - 0.49Y	-24 cm	P<0.002

*NS indicates that trend is not significant (P > 0.05)

Regression analysis of climate trends for stations near the CIPHA sites (Table 5) gave results that were consistent with those reported earlier. Over the period 1951-2000, overall mean temperature showed a significant increase of 1.7ºC, with slightly more rapid warming of daily minimum temperatures than daily maximum temperatures. The increase in the number of growing degree days (+109) over the 50-year period was nearly as great as the long-term mean difference of 129 between the boreal (1143) and parkland (1272) sites. In contrast, there was no evidence of regional change in the moisture regime during this period, with no statistically significant trends for either total precipitation or the Climate Moisture Index (Table 5).



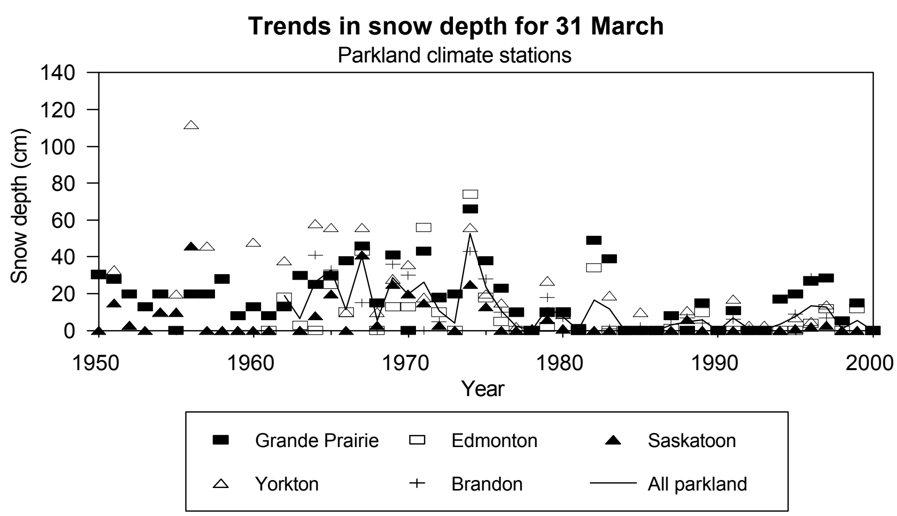


Figure 7. Annual records of snow depth for late winter (31 March) at climate stations in the boreal and parkland zones of the CIPHA study region. Lines show changes in average snow depth for the period when data were available for all five of the climate stations in each zone.

Trends in late winter snow depth at selected climate stations

Although snow depth data were available for relatively few climate stations, there was evidence of a significant trend toward reduced snow depth in late winter, based on average data from five stations in the CIPHA study region for the period 1951-2000 (Table 5). The magnitude of the decrease (-24 cm) was greatest for snow depth on 31 March. The pattern of change in snow depth for this date is shown in Figure 7, which also includes data from other stations with a shorter period of record. The most striking change is apparent in the data from the parkland, which show that prior to 1977, there was usually a significant snow pack on 31 March, but since 1977, conditions have been generally snow free on this date at most of the stations. In a previous study of aspen in the Grande Prairie area of northwestern Alberta (Hogg et al. submitted), we concluded that light snow cover in late winter may have contributed to aspen forest dieback, through increased exposure of roots to soil thaw-freeze events during the early 1990s. We also found a significant positive relationship between aspen tree-ring growth and snow depth on 31 March. Although we have not conducted a similar analysis for the present study, further study is warranted on the potential impacts of reduced late-winter snow depth on the growth and health of aspen forests in this region.

Potential for hail damage

Figure 8 shows the hail frequencies from May to September for the period 1977-1993 over the Prairie Provinces. Pockets of high frequencies (3-9 days per year per degree area) occur east of the Rocky Mountains in Alberta. The influence of topography is evident, with the maxima occurring over the higher terrain features. Hail frequencies are typically less than 2 days per year in Saskatchewan and Manitoba. These analyses indicate that most of the CIPHA study region is located in a relatively low hail frequency belt. Nevertheless, the observed occurrence of hail damage to aspen at two of the CIPHA sites (Dunvegan and Glaslyn, locations shown in Figure 1) suggests that hail poses a significant future risk for aspen forests, especially in the western portions of the study area.

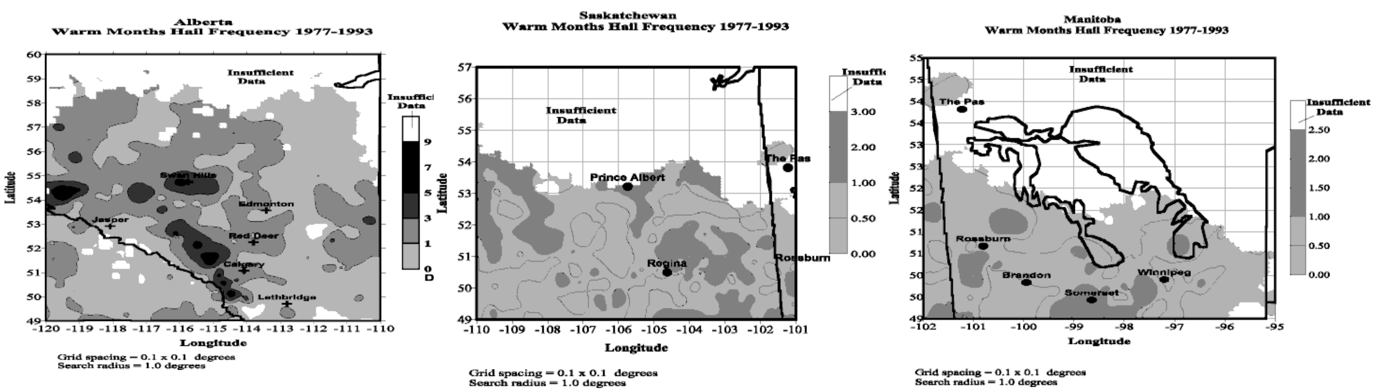


Figure 8. The average number of hail days per warm season (May-September) for Alberta, Saskatchewan and Manitora during the period 1977-1993. A Kriging algorithm (with a linear variogram) using a 1degree search radius was used to produce a 0.1x0.1 degree set of grid cells from the rawstation data. Figure courtesy of D. Etkin.

Conclusions and future directions

The results of the first phase of the CIPHA study show that aspen growth in the western Canadian interior has undergone several cycles of reduced growth followed by recovery during the period 1950-2000. Preliminary analyses of tree-rings at the 24 study sites indicates that insect defoliation and drought are the most important factors driving year-to-year variation in aspen productivity, but other climatic factors such as reduced late winter snow depth, thaw-freeze events and hail are likely to exert significant local impacts. A wide variety of damage agents was also recorded, including wood-boring insects and fungal diseases, and the occurrence of damage and crown dieback was generally greater in the warm, dry parkland sites than in the cooler and moister boreal sites. Despite their similar average age (60 years old), the aspen in the parkland zone was found to be generally stunted, with smaller stand basal areas than aspen in the boreal zone.

The analyses also indicate that aspen growth was generally reduced during and after the unusually warm year of 1998, which was also one of the driest years on record over some parts of Alberta and Saskatchewan. At this stage of the study, there is no indication that aspen productivity is increasing in response to the recent climatic warming that has occurred in this region.

Currently (July 2001), the second year of forest health assessments are in progress at the CIPHA sites with support from other funding agencies and collaborators. The results will be used to determine how the unusually warm, dry winter of 2000-2001 has affected tree mortality and dieback across the region. The analysis of disks collected at various heights will be completed during the winter of 2001-2002, which will be used to determine aboveground net primary productivity at each site. In future years (2002-2005), the annual forest health assessments will be continued, and tree-ring analysis will be repeated at least once during this period.

Opportunities for increasing the scope of CIPHA study are currently being pursued and implemented. Leaf litter traps are being installed at CIPHA sites to determine a) species composition of the tree and shrub layers, b) carbon input of leaf biomass into the soil litter layer, and c) leaf area index (key indicator of forest health and productivity for remote sensing and simulation modelling). A pilot study is also being undertaken in collaboration with the remote sensing community (Ron Hall and others), to examine how remote sensing may be applied for large-scale monitoring of defoliation and dieback of aspen. There are also plans to conduct soil analyses and measurements of carbon pools in the soil, litter and woody debris at CIPHA sites (collaboration with J.S. Bhatti). During 2001, CIPHA methodolies were also implemented by research collaborators (Great Lakes Forestry Centre and Ontario Ministry of Natural Resources) to establish monitoring plots near Timmins, Ontario, where severe aspen dieback has been recently noted.

A key future component of CIPHA will be the validation, improvement and application of climate-driven simulation models of forest productivity, mortality and carbon sequestration. Initially, results will be used to apply a model specifically developed for simulating aspen responses to climate change and insect defoliation (Hogg 1998). We will also apply the results in future collaborative efforts to improve the functional realism of forest responses within other regional and national modeling initiatives, e.g., integrative climate change modeling (D.T. Price), the carbon budget model (Apps and Kurz) and ECOLEAP (Bernier). Model predictions of aspen biomass growth, stem mortality and leaf area index will be tested against the measurements at each site. Scenarios of climate change and associated changes in insect defoliation frequency will then be applied to assess how aspen growth and dieback is likely to be affected in future at the regional scale.

Acknowledgements

This work was conducted through funding support from the Government of Canada's Climate Change Action Fund, ENFOR, the Climate Change and Forest Health Networks of the Canadian Forest Service, Natural Resources Canada, and through a Collaborative Research Agreement with Mistik Management Ltd., Meadow Lake, Saskatchewan. Tree-ring measurements were conducted by Trisha Hook, and analyses of aspen growth and health data were conducted by Mike Michaelian. Field operations were conducted by Roger Brett, James Hammond, Trisha Hook, Mike Michaelian, Brad Tomm and Jim Weber, with field and laboratory assistance by Amber Engel, Ryan Raypold, Dan Sherling, Bryan Vroom, Catherine Charmin, Adam Gossell, Amanda Hamelink and Tracy Young. Climate data were provided with the assistance of David Etkin, Len Fehr, Patrick Kyle, Thanh-Van Nguyen and others at Environment Canada. We also acknowledge the cooperation of the many government and non-government land management agencies and their representatives who have assisted in various ways with the CIPHA study, with special thanks to Roger Nesdoly, Ecosystems Research Coordinator at Mistik Management Ltd., and Dave Wieder, BERMS site manager in Prince Albert National Park.

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