VARIATIONS IN BOREAL FOREST FIRE FREQUENCY

SPATIAL AND TEMPORAL VARIATIONS IN FIRE FREQUENCY IN THE BOREAL FOREST OF NORTHERN ALBERTA

By

CHRISTOPHER POUL STORM LARSEN, M.Sc.

A Thesis
Submitted to the School of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree
Doctor of Philosophy

DOCTOR OF PHILOSOPHY (1994)
(Geography)

McMASTER UNIVERSITY
Hamilton, Ontario

TITLE: Spatial and Temporal Variations in Forest Fire Frequency in the Boreal Forest of Northern Alberta.

AUTHOR: Christopher Poul Storm Larsen, M.Sc.

SUPERVISOR: Dr. G.M. MacDonald

NUMBER OF PAGES: xiv, 154

ABSTRACT

Forest fires occur frequently in the boreal forest of North America and greatly affect vegetation dynamics, biogeochemical cycles and resident human populations. Estimates of the frequency of boreal forest fires would be useful for understanding boreal ecosystems and managing the affects of fires on human populations. The objectives of this work were to investigate relations between fire frequency and climate change, vegetation type and waterbreaks in Wood Buffalo National Park (WBNP), located in northern Alberta. To address these objectives, four hypotheses were tested: 1) tree ring-width records from the boreal forest can provide a proxy climate record; 2) annual area burned in the boreal forest varies in response to climate changes; 3) boreal forest fire frequency varies with differences in forest type and the proximity to waterbreaks; and 4) fossil pollen and macroscopic charcoal records from massive lake sediments can provide meaningful estimates of local fire frequency.

The first hypothesis was tested by constructing tree ring chronologies from 3 white spruce and two jack pine sites in WBNP. All five chronologies were significantly positively correlated with June precipitation in the growth year or the previous year, and were significantly negatively correlated with historical records of fire weather and annual area burned.

The second hypothesis was tested by analyzing historical records of annual area burned and climate, and tree ring records of fire history and climate. Annual area burned was significantly negatively correlated with seasonal means of fire weather indices. The time since last fire was estimated using tree ring records from 166 sites located throughout WBNP. These records exhibited decadal and centennial scale variations in fire frequency. Comparisons with tree ring other proxy climate records suggest that these variations are related to climatic changes.

The third hypothesis was tested using survival analysis of the time since last fire records, disaggregated by dominant vegetation and the mean distance to waterbreaks. Sites dominated by jack pine (*Pinus banksiana*) and aspen (*Populus tremuloides*) exhibited significantly higher fire frequencies than did sites dominated by black spruce (*Picea mariana*) or white spruce (*Picea glauca*). Fire frequency increased with increased mean distance to waterbreaks.

The fourth hypothesis was tested by analyzing fossil pollen and charcoal records from two lakes at $\sim$5 year resolution for 600 years. I compared their fire history records with local tree ring records of fire, and their mean fire intervals with regional fire frequency estimates for sites with similar vegetation and mean distances to waterbreaks. One lake exhibited a meaningful fire frequency estimate and the other lake did not. The poor fire frequency estimate was related to high sediment mixing and the lack of homogenous vegetation around the lake.

The results indicate that: 1) area burned and fire frequency in the boreal forest of northern Alberta varies temporally at the annual, decadal and centennial scales; 2) fire frequency varies spatially in relation to vegetation type and mean waterbreak distance; and 3) lakes with massive sediments can provide meaningful estimates of local fire frequency.

ACKNOWLEDGEMENTS

Many people have contributed in many ways to the development of this dissertation. Funding for the research was provided through a contract from Parks Canada, through McMaster Geography Departmental scholarships, a University of Waterloo Institute for Risk Research Scholarship, and Northern Supplement Grants to Chris Larsen, and NSERC operating and equipment grants to Glen MacDonald.

I am grateful for field help from Mark Heathcott, Mike Hutton, Lee Keary, Carl Laferty, Katrina Moser, Julian Szeicz and Mike Wynn. Thanks also to Dave Porinchu and Shirin Mehrain for laboratory help.

The help of the support staff at the Geography Department has been exceptional. Many thanks to Bob Bignell, Cliff Brettle, Medi Espiritu, Ric Hamilton, Joan Parker and Darlene Watson for their constant, careful help.

My friends have provided great relief from the strains of academic life. Hugs to Jorge Bonilla, Shereen Dennetto, Allison Diamond, Farzana Doctor, Mark Jeffreys and Stef MacLachlan.

Lab mates (Julian Szeicz, Katrina Moser, Roslyn Case, Katherine McLeod) and lab rats (Andrea Litva, Shannon Glenn) made it alot of fun. I miss you all.

My supervisory committee was very helpful in the formulation, operatonalization and analysis of my research. Thanks to Terry Carleton, Carolyn Eyles, Glen MacDonald and Wayne Rouse.

My deepist gratitude is reserved for my parents (Rona and Viggo Larsen), my wife (Fariya Doctor) and my mentor (Glen MacDonald). Words fail.

This one goes out to the one I love

This one goes out to the ones that I left behind

A simple prop to occupy my time

This one goes out to the one I love

FIRE! FIRE!

Michael Stipe

We have to call for a knife, which is the gift of those who came before us, a strong knife, the end simpleminded but without Puritanism, it arranges its hard-ended molecules so as to recapture the past, gallop up the valley, return the dead to their former lives.

Robert Bly

TABLE OF CONTENTS

LIST OF FIGURES

Figure

LIST OF TABLES

Table

CHAPTER ONE

INTRODUCTION

1.1 RATIONALE FOR STUDY

Wildfires are a frequent, natural force of disturbance in the boreal forest of North America. The size, power and frequency of these fires results in them markedly affecting ecological processes (Viereck 1973, Bonan and Shugart 1989). Fires are typically large, with burns of up to 14,000 km^2 having been observed, and with fires greater than 2 km^2 accounting for most (~ 97%) of the area burned (Johnson 1992). The mean fire frequency in the Canadian boreal forest has been suggested to be ~100 years (Johnson 1992). Note that fire frequency may refer to either the mean fire interval (MFI) or the fire cycle (the number of years required to burn an area equal in size to the study area); in most cases these measures are equivalent (Johnson and Van Wagner 1985). The term fire frequency will be used throughout this work except when a specific estimate is mentioned, in which case it will be noted whether it is of the MFI or the fire cycle.

Boreal forest fires are typically of such a high intensity that all vegetation in their path is combusted or killed (Viereck 1973). Following a fire there is a pulse of plant establishment, followed by successional changes in species presence and abundance (eg. Heinselman 1981, Johnson 1981). Coincident changes in the presence and abundance of fauna (eg. animals, birds and insects) which use the vegetation for food or shelter may also occur (Viereck 1973, Bendell 1974). The combustion of vegetation also affects biogeochemical cycling with nutrients immediately lost in the form of smoke and gasses during combustion, and later lost as leachate from the residual ash (eg. Evans and Allen 1971, Moore 1980). Nutrient leachates from the site may continue to vary in response to successional changes in the forest composition (Van Cleve and Viereck 1981, Vitouseck 1988). These changes in biogeochemical cycling may alter aquatic ecosystems (Minshall et al. 1989, Bayley et al. 1992).

The burning of boreal forests can also strongly impact on resident human populations and their economic activities (Tiedemann 1981). Fires can burn valuable infrastructure and timber holdings, while smoke can cause health problems and disrupt transportation over large areas.

It is believed that fire frequency varies temporally in response to climate change (eg. Johnson and Larsen 1991, Bergeron and Archembault 1993) and spatially in response to factors such as vegetation type and the presence of topographic breaks and water bodies which will slow or stop the spread of fires (eg. Zackrisson 1977, Yarie 1981). Knowledge of temporal and spatial variations in fire frequency would be useful for resource management planning (eg. Martell 1983, Reed and Errico 1986) and for understanding relations between forest disturbance and community diversity (Suffling 1983, Suffling et al. 1988). This knowledge should also be useful for understanding possible effects of hypothesized global warming on the boreal forest (Overpeck et al. 1990, Antonovski et al. 1992, Rizzo and Wiken 1992).

Retrospective studies of fire history through analysis of forest age structure (eg. Johnson and Van Wagner 1985) and fossils of pollen and charcoal in lake sediments (eg. MacDonald et al. 1991) can provide useful methods to examine whether there have been temporal or spatial variations in fire frequency. Wood Buffalo National Park (WBNP), located in northern Alberta, provides an excellent location to study temporal and spatial variations in boreal forest fire frequency. First, the area has a high fire-climate hazard (Simard 1975). Second, the area has few roads and there are therefore few human ignited fires. Third, since the area is remote and is a National Park, fire control has been minimal.

1.2 CONTROLS ON BOREAL FOREST FIRES

Fire frequency is a function of the number of fire ignitions and the area burned by the ignited fires. Fire ignitions by humans account at present for at most 10% of the area burned in the Canadian boreal forest (Johnson 1992). Natives formerly burned small areas of wetland to improve browse and small areas of upland forest to ease transport (Lewis 1977), but since they were careful to not burn large areas it is likely that they burned less area than humans affect at present. The most important source of fire ignitions in the boreal forest is lightning. The number of lightning ignited fires increases with the number of lightning discharges and the dryness of the forest fuels (Flannigan and Wotton 1991). There is some evidence that lightning ignites more fires in certain landscape positions and forest types than in others, due to their respective relations with storm tracks and fuel flammabilty (eg. Fowler and

Asleson 1984, Quinby 1987), but the results are not clear because of the short duration and small area of the studies.

The amount of area burned by a fire is a function of weather conditions, forest type, topography and fuel breaks. Dry weather increases fuel dryness thereby increasing the efficiency of fuel combustion and the amount of heat released by a fire, while increased wind speeds allow a rapid spread of the fire front (Van Wagner 1987). Different forest types exhibit different rates of fire spread under the same weather conditions because of differences in factors such as fuel quality (eg. deciduous or coniferous), fuel structure (eg. whether or not there is a ladder of fuel from crown to ground), and fuel dryness (wet or dry sites) (Forestry Canada 1992). The rate of spread of a fire increases on uphills because flames bend upslope thereby increasing radiant heat transfer, while this same effect causes the rate of spread to decline on downills (Van Wagner 1988). Fuelbreaks, typically in the form of waterbodies, can slow or stop the spread of fires. Fuelbreaks of 1 to 2 metres can stop small fires, while breaks of up to 30 metres are required to stop large fires (Davis 1959). The front of a very large fire may be stopped by a fuelbreak, but strong winds can blow burning brands to form spot fires several kilometres in advance of the front, resulting in the rate of spread of the fire only being slowed by the fuelbreak (Chandler et al. 1983).

It has been suggested that large fires (Newark 1975, Street and Birch 1986) and large fire years (Johnson and Wowchuk 1993) are typically associated with the presence and breakdown of blocking high pressure systems. Little rain occurs in areas dominated by a blocking high, resulting in dry forest fuels. When the blocking high pressure system breaks down there are many lightning strikes which can ignite the dry fuels, and strong winds which lead to very rapid rates of fire spread. If the fuels are very dry a fire may survive the rainfall which also accompanies the breakdown of the high pressure system, with the fires sometimes continuing to burn for the rest of the summer and autumn. Relations between records of weather and area burned at the monthly and annual scale confirm these patterns between extended drought, synoptic conditions and area burned (Flannigan and Harrington 1988, Johnson and Wowchuk 1993).

1.3 RETROSPECTIVE STUDIES OF BOREAL FOREST FIRE FREQUENCY

Retrospective studies of fire history in the boreal forest have been employed to determine the mean fire frequency for a region and to determine if fire frequency changes in response to variations in the site conditions which control fire behaviour. It is expected that fire frequency should be higher in sites which have conditions which lead to more extreme fire behaviour, and in time periods during which climate was more conducive to extreme fire behaviour. Fire history studies typically employ either dendrochronological analysis of tree ring records from living trees, often in combination with historical fire records, or palaeoecological analysis of fossil pollen and charcoal in lake sediments.

1.3.1 Dendrochronological studies

Fire frequency is estimated from tree ring records using fire scars or forest age data. Fire scars are formed when the heat of a fire kills part of the cambial growth layer under the bark of a tree (McBride 1983). Since annual growth rings will only be formed where the cambium survives, the number of growth rings between successive fire scars indicates the fire interval. In areas where fires are typically of low intensity, a tree may contain tens of fire scars (eg. Swetnam 1993). The distribution of fire intervals can be statistically analyzed to estimate the mean fire interval (MFI) (eg. Clark 1990). If enough stands with multiple fire scar records are available, it is possible to assess changes in fire frequency due to changes in site differences or climate (eg. Clark 1990, Swetnam and Betancourt 1990, Swetnam 1993).

In the boreal forest the high intensity fire regime typically precludes the preservation of long fire scar records (but see Carroll and Bliss 1982). The fire frequency can be estimated, however, by determining the time since last fire (TSLF) from stands throughout the region using fire records, fire scars and canopy tree establishment ages. Canopy tree establishment ages can indicate the TSLF in the boreal forest since trees there typically become established within several years of the fire (eg. Johnson and Fryer 1989, St-Pierre et al. 1992). The TSLF can be determined for a random sample of stands throughout the region (eg. Yarie 1981, Bergeron 1991) or, if sampling is sufficiently dense and tree growth rates are similar across the landscape, the TSLF can be mapped for the entire area (eg. Heinselman

1973, Johnson and Larsen 1991). The TSLF estimates can be plotted as a survival distribution, and estimates of fire cycle can be obtained from it using a combination of graphical and statistical methods (Johnson and Van Wagner 1985). When the fire interval or TSLF data conform to a negative exponential distribution, as they do in most studies (eg. Yarie 1981, Masters 1990, Bergeron 1991, Johnson and Larsen 1991), the MFI and fire cycle will be equal (Johnson and Van Wagner 1985).

Analyses of TSLF data from the boreal forest regions have suggested that pine and aspen forests burn more frequently than spruce forests (eg. Zackrisson 1977, Yarie 1981, Cogbill 1985), dry sites burn more than mesic sites (Zackrisson 1977, Suffling et al. 1982), and fire frequency decreases with increases in topographic variation and the number of waterbodies (eg. Johnson 1979, Foster 1983, Bergeron 1991). The fire cycle estimates in these studies ranged between 37 and 183 years. The estimates are less variable within one study region with, for example, the fire cycle estimates from the interior of Alaska ranging only from 60 years in aspen forests to 113 years in white spruce forests (Yarie 1981). It is important to note that the variations in fire frequency by forest or site type suggested by these studies were typically based on either informal observations (eg. Foster 1983), or a non-statistical comparison of the mean ages of stands (eg. Zackrisson 1977, Johnson 1979, Yarie 1981, Suffling et al. 1982, Cogbill 1985, Bergeron 1991). Statistical tests which assess whether mean forest ages are significantly different, such as recently introduced to fire history research by Clark (1989), are required before the variations in fire frequency suggested by these authors can properly be accepted.

It has been suggested in a number of boreal fire history studies that TSLF records exhibit pulses of forest establishment indicative of episodic variations in fire frequency (eg. Rowe et al. 1974, Foster 1983, Bergeron and Archembault 1993). Such variations are not unexpected, since co-variations in climate and annual area burned have been found from analysis of hisorical records from non-boreal forests (eg. Swetnam and Betancourt 1990, Johnson and Wowchuk 1993). The testing of this suggestion using TSLF records has proven difficult, however, since recent fires overburn stands originating from previous fires, limiting the knowledge of actual area burned from TSLF records to the most recent fires. Bergeron and Archembault (1993) found that what appeared to have been large fire years in the TSLF records were significantly correlated with tree ring records of drought. Other authors have tried to reconstruct the area originally burned by now overburned fires by piecing together the remaining portions of forest that were burned in the same year (eg. Heinselman 1973). However, this method neglects the fact that large fire years typically exhibit numerous large fires, and as a result the method could lead to an overestimate of the area burned in a single year.

1.3.2 Palaeoecological studies

Analyses of fossil pollen and charcoal from lake sediments have been used to reconstruct the local fire history of a number of boreal and non-boreal forest sites (eg. Swain 1973, 1978, 1980, Cwynar 1978, Patterson and Backman 1988, Clark et al. 1989, Clark 1990, MacDonald et al. 1991). An estimate of the fire frequency from one site potentially allows the effect that site specific variables can have on fire frequency to be rigorously controlled. In addition, such studies allow the estimation of the pre-historic fire frequency of sites that have been markedly affected by humans actions such as fire control or logging. There are a number of technical problems that have limited the quality of fire history reconstructions, with the major problems being related to charcoal source area, the nature of vegetation succession, pollen source area, and chronology construction.

The early palaeo-fire studies typically inferred the occurrence of local fires as peaks in microscopic charcoal and/or declines in local tree pollen along with increases in pollen from early successional plant taxa (eg. Swain 1973, 1978, 1980, Cwynar 1978, Patterson and Backman 1988). In some cases these methods provided clear records of known local fires, while other times they did not (see examples in Patterson and Backman 1988). This problem in part likely stems from the use of microscopic charcoal as an indicator of local fires, the use of which has recently been criticized based on aerodynamic principles (Clark 1988). These principles suggest that little of the microscopic charcoal (typically $<100\mu m^2$) will be deposited locally and that much of it will be lofted tens to hundreds of kilometres from the site of combustion. In contrast, the aerodynamic principles suggest that macroscopic charcoal (typically $>2000\mu m^2$) should be deposited very close to the site of combustion. The local nature of peaks in macroscopic charcoal and the potentially regional source of microscopic charcoal has been supported by empirical research (Clark 1990, MacDonald et al. 1991). It should be noted that the macroscopic charcoal is physically destroyed during the processing of sediment samples for pollen analysis.

There are also potential problems with the use of pollen records of post-fire succession of surrounding vegetation succession to mark fire occurrences. I define succession as the change in absolute and relative abundance of a plant taxa in a site over time. Early studies by forest ecologists of succession in the North American boreal forest suggested that succession followed a simple pathway from a post-fire plant community dominated by herbs to a late successional communty dominated by spruce (eg. Cooper 1913). Later studies by forest ecologists recognized that, depending on the fire characteristics and the availability of plant propagules, there can be a great variabilty in the plants that become established following a fire (eg. Rowe 1983, McCune and Allen 1985). Further, it was recognized that most of the trees which dominate the late successional community become established at the site immedately following the fire, not several decades later, and have late dominance because of slow growth rates (eg. Loehle 1988, Johnson and Fryer 1989). It is likely that, despite the variability in post-fire successional paths which occurs at the species level in the boreal forest, at the landscape scale at which lakes sense pollen from the surrounding forest, most successional paths should exhibit a change in dominance from herbs to shrubs to trees. However, it is important that fossil pollen analyses should carefully examine the successional patterns forest ecologists have found in the forest type that surrounds the lake being analyzed.

The occurrence of post-fire vegetation succession does not, however, ensure that it will be recorded in the fossil pollen record. The size of the area surrounding the lake sensed in the fossil pollen record is affected by the surface area of the lake and the buoyancy of the pollen grain (Prentice 1985, Sugita 1993, Sugita in press). Since most of the pollen produced by a tree falls closest to the tree, smaller lakes will have more local pollen deposited in them than will larger lakes. Similarly, dense pollen will be deposited closer to its source than will more buoyant pollen types. Based on theoretical, empirical and simulation studies, it has been suggested that lakes with a radius of less than 250 metres should have a large enough local pollen source (< 800 metre radius) that changes in the local vegetation can be sensed in the fossil pollen record.

To resolve fire events and post-fire succession, and to calibrate these with local forest evidence of fires and succesion, a sediment chronology is required. Most palaeo-fire studies have employed lake sediments that are annually laminated, since these laminations provide excellent dating control. The reliance on laminated sediments presents a limitation, though, since such lakes are rare (Larsen and MacDonald 1993), making the use of these methods limited in scope. Palaeo-fire studies employing massive (non-laminated) lake sediments have been undertaken. Such studies have in some cases been able to infer known local fires from the fossil record (eg. Swain 1980, Patterson and Backman 1988), but the fire frequency estimates obtained from such studies have not been validated against a more reliable dendrochronological fire frequency estimate. Such validation is required before the method can be judged reliable enough for the estimation of the fire frequency in sites with an unknown fire frequency.

1.4 RESEARCH OBJECTIVES

The objectives of this study are to estimate the mean fire frequency of the boreal forest of northern Alberta and to investigate whether the fire frequency varies in response to factors that are known to affect fire behaviour. From the review of retrospective studies of fire frequency, it is clear that the results obtained in previous studies with similar objectives have often been limited by methodological problems. In this research I attempt to improve methodologies for estimating the fire frequency, and test four specific hypotheses regarding boreal forest fire frequency:

1) Tree ring-width records from the boreal forest provide a proxy record of climate.

To determine if fire frequency varied in response to past climatic variations, it is necessary to have a long climate record from the same location. Monthly climate records from Fort Smith NWT, located on the northeastern outside edge of WBNP, begin in 1913 but are not continuous until 1922. Climate records from Fort Chipewyan, Alberta, located on the southeastern outside edge of WBNP, begin in 1883 but are not continuous until 1963. It was hypothesized that tree ring width records from trees in old stands of forest within WBNP could provide a proxy record of past climate. Previous dendroclimatic research in the boreal forest had found significant positive correlations between annual ring width and summer precipitation and significant negative correlations with summer temperature (Dang and Lieffers 1989, Archambault and Bergeron 1992). Archambault and Bergeron (1992) also found a significant correlation between annual ring width and a fire climate variable. In a study from outside of the boreal forest, Swetnam and Betancourt (1990) found a significant correlation between annual ring width and annual area burned. It may therefore be possible to link tree ring width records with climate, fire climate and annual area burned. In addition, it was examined whether spruce budworm activity may have affected the tree ring width records. The hypothesis will be rejected if correlation analyses find no significant relations between annual tree ring width records, climate records and annual area burned.

2) Annual area burned in the boreal forest varies in response to climate changes.

The importance of climate variations in altering boreal forest fire frequency has been suggested by various studies (eg. Rowe et al. 1974, Bergeron and Archembault 1993), but has not clearly been proven. To test this hypothesis I develop a dendrochronological fire history of WBNP. I then apply life table analysis and logarithmic regression to the fire history data to reconstruct the past variations in annual area burned in WBNP. In addition, I present historical records of annual area burned in WBNP between 1950 and 1989. If the dendrochronological and historical records of annual area burned are not significantly correlated with historical climate records and local tree ring records, and if there is no significant change in fire frequency around the end of the Little Ice Age in the mid-19th c., this hypothesis will be rejected.

3) Boreal forest fire frequency varies with differences in forest type and the proximity to waterbreaks.

Differences in fire frequency by vegetation type and the proximity to water breaks have been suggested by many boreal forest fire history studies (eg. Zackrisson 1977, Yarie 1981, Foster 1983, Bergeron 1991), but have not yet been statistically proven. To test this hypothesis I disaggregate the fire history data for WBNP into classes with different dominant forest trees and different mean distances to waterbreaks. Survival analysis methods are used to estimate the fire cycle for the different vegetation and waterbreak classes, and to determine if the estimates are significantly different. The hypothesis will be rejected if the fire cycle estimates are not significantly different.

4) Fossil pollen and macroscopic charcoal records from massive lake sediments can provide meaningful estimates of local fire frequency.

It would be valuable to be able to know the fire frequency of specific sites. Fossil pollen and macroscopic charcoal records from lakes with massive sediments could offer the ability to obtain site specific estimates of the mean fire interval (MFI). Previous research has been hampered by the use of microscopic charcoal and the lack of dendrochronological fire frequency estimates for the site type with which the MFI estimates can be validated. I will estimate the palaeo-MFI from two different sites using fossil pollen and macroscopic charcoal records from lakes with massive sediments. This hypothesis will be rejected if the palaeo- MFI estimates obtained for both sites are not consistent with the dendrochronological fire cycle estimates obtained from sites in WBNP which have similar vegetation dominants and mean distances to waterbreaks.

CHAPTER TWO

RELATIONS BETWEEN TREE RING WIDTHS, CLIMATE, SPRUCE BUDWORM ACTIVITY AND FIRE IN NORTHERN ALBERTA[1]

2.1 INTRODUCTION

Forest fires and defoliation by the spruce budworm (*Choristoneura fumiferana* (Clem.)) are the two most important natural agents of disturbance in the boreal forest of Canada (Forestry Canada 1990). Warm and dry summer weather has been related with increased monthly area burned (Harrington et al. 1983, Flannigan and Van Wagner 1991) and increased spruce budworm activity (Greenbank 1956. Volney and Cerezke 1992). It is therefore expected that should the CO_2 induced global warming predicted by computer models occur (Houghton et al. 1990), disturbance in the boreal forest will increase (eg. Flannigan and Van Wagner 1991). However, because observational records of climate, fire and particularly spruce budworm activity are short for most areas, it is difficult to determine the relations between climatic variation and disturbance frequency. Tree rings can provide the proxy records of climate (Fritts 1976), fire (Bergeron and Archambault 1993) and spruce budworm activity (Swetnam and Lynch 1989) required to examine relations between climate and disturbance frequency.

---

[1] A modified version of this chapter, authored by C.P.S. Larsen and G.M. MacDonald, as been submitted to **Canadian Journal of Forest Research**.

There have been few dendroclimate studies in the central boreal forest of North America (Luckman and Innes 1991). Dendroclimate studies that have been undertaken in the central boreal forest have found significant positive correlations between annual ring width and summer precipitation and significant negative correlations with summer temperature (Dang and Lieffers 1989, Archambault and Bergeron 1992). In addition, Archambault and Bergeron (1992) found a significant correlation between annual tree ring width and the maximum summer value of the Drought Code, a fire weather variable correlated with fire activity (Harrington et al. 1983).

Tree- ring records from Quebec and Ontario, where spruce budworm defoliation can be severe, have been used to reconstruct the timing and frequency of past spruce budworm outbreaks (eg. Blais 1954, 1983, Morin et al. 1993). In western Canada spruce budworm defoliation is not as severe and tree-ring records have not been used to examine the timing and frequency of past spruce budworm outbreaks.

In this initial study I assess the ability of tree-ring records from the central boreal forest of northern Alberta to provide proxy records of climate, fire and spruce budworm activity. We first investigate the climate - radial growth relations for *Picea glauca* (Moench) Voss (white spruce) and *Pinus banksiana* Lamb. (jack pine) using response function and multple linear regression analysis. The white spruce chronologies are then examined for evidence of past spruce budworm outbreaks. Finally, I determine the strength of relations between the ring-width chronologies and historical records of fire weather and fire activity.

2.2 STUDY AREA

Tree-ring collections were made from five stands located in the central boreal forest of Wood Buffalo National Park (WBNP) (Fig. 2.1). The Salt Flat (SF), Rainbow Lake (RL) and Bad Road (BR) sites were white spruce stands on silty soils, and the Parsons Road (PR) and Ninisith Lake (NL) sites were jack pine stands on sandy soils. The sites all had closed canopies and very well drained soils. The NL site had hilly topography due to the presence of sand eskers, while the terrain at the other four sites was flat or gently sloping. These sites were the oldest upland white spruce and jack pine stands that could be found in the area.

Climate normals (1951-80) (Environment Canada 1982) are available for Fort Smith, N.W.T. (60° 00' N and 111° 55' W, Fig. 2.1). The mean annual temperature is -3.3 °C. Mean monthly temperatures are above 0 °C from May to September and the warmest month (July) reaches 16°C. The mean annual precipitation was 36.5 cm, with 21.0 cm falling during the 5 (summer) months with mean temperatures above 0°C.

Fire records have been kept for the 44,807 km^2 area of WBNP since 1950 (WBNP Warden unpublished file). Annual area burned (AAB) is quite variable, ranging from 0.001 km^2 in 1962 to 6519 km^2 in 1981. The mean fire interval (the average interval between consecutive fire events at any location) in WBNP was approximately 63 years for the period between 1860 and 1989 (Chapter 4).

Observations of spruce budworm activity in the WBNP area have been made as part of the Forest Insect and Disease Survey (FIDS) by the Canada Department of

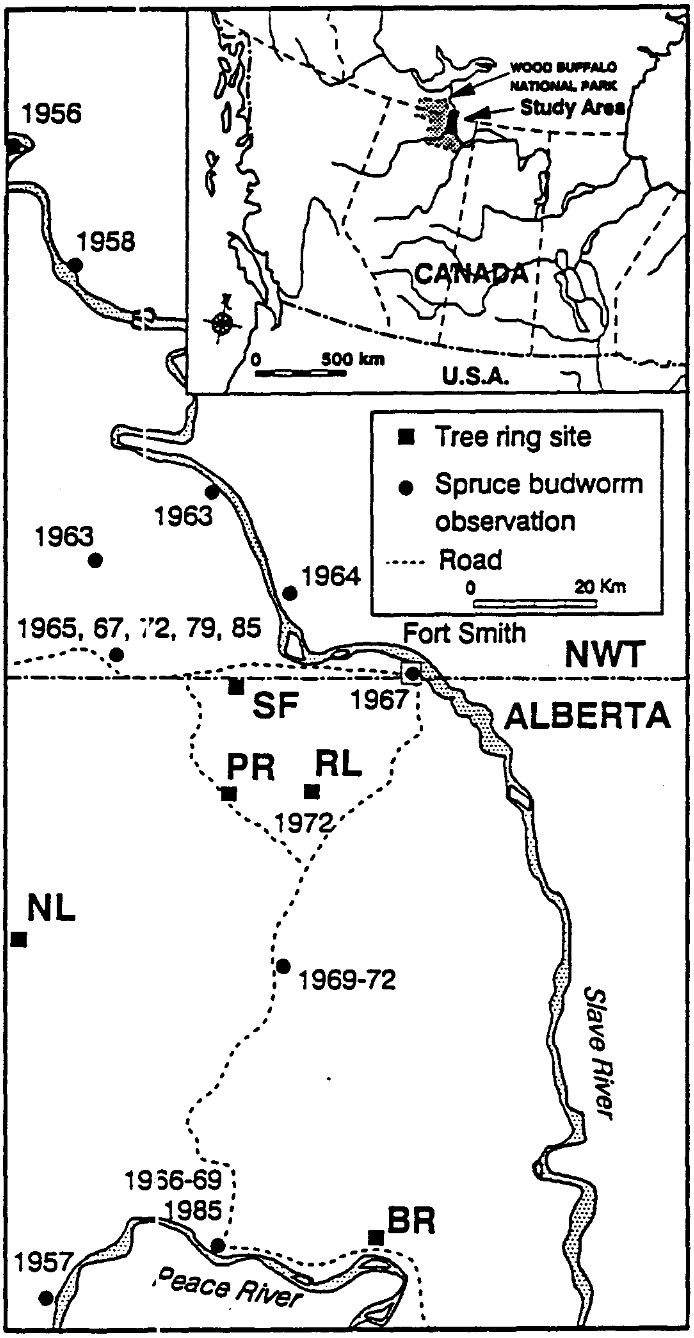

Figure 2.1. Study area with tree ring sites (■) and spruce budworm observations (●). The tree ring sites are: Salt Flats (SF), Rainbow Lake (RL), Bad Road (BR), Parsons Road and Ninisith Lake(NL). Dates on the map indicate years in which the FIDS records indicate that spruce budworm activity was observed at that site.

Fisheries and Forestry. Spruce budworm larvae feed on needles and cones, thereby reducing the vigour of trees (Royama 1984). The only other insect infestation of any tree species that was noted more than once in WBNP in the FIDS records were endemic spruce beetle (*Dendroctus rufipennis* (Kby.)) infestations on white spruce deadfall along the Peace River in 1963, 1983, 1985 and 1986, and observations of the yellow-headed spruce sawfly (*Pikonema alaskensis* (Roh.)) in whte spruce stands around Ft. Smith in 1956, 1962 and 1963.

The first report of spruce budworm activity in the NWT was made in 1947, and the first mention of spruce budworm activity in the present study area was made in 1956. FID surveys were made every year on the ground and using fixed wing aircraft, but were typically of low intensity until a severe defoliaton event was known (H. Cerezke per. comm.). As a result, the record of a defoliation event is typically poor at its beginning but improves in subsequent years. It should also be noted that the mapping of defoliation events was often of poor quality because of the lack of distinct landmarks (H. Cerezke, per. comm.). Although the FIDS records are therefore not of the highest quality, they should record the multi-year defoliation events which cover tens of kilometres.

All recorded FIDS observations of spruce budworm activity within the study area are shown in Fig. 2.1. The defoliation events that occurred north of Fort Smith prior to 1967 were of moderate to severe intenstiy, but all the rest were of light intensity. A defoliation event is classified as light if only the top 1 to 2 metres of the tree crowns show defoliation, moderate if 1/2 the tree crowns show complete defoliation, and severe if all the trees in an area are completely defoliated (H. Cerezke per. comm.). The only spatially extensive spruce budworm outbreak in the WBNP area noted in the FIDS records occurred between 1966 and 1971 (Fig. 2.1). Although this outbreak covered upwards of 350 km^2 of WBNP in 1967 and 1100 km^2 in 1968 (Canada Department of Fisheries and Forestry 1969), the defoliation in all years was only of light intensty. The extent of this major defoliation event was not mapped, so it is not known if it covered the sites from which the tree ring chronologies were collected.

2.3 METHODS

2.3.1 Chronology construction

Cores were collected at knee to breast height from 10 to 28 canopy trees at each of the five sites (Table 2.1). Two cores ~90° to each other were extracted from most white spruce trees and one core was extracted from each pine tree. Ring widths were measured with a Velmex UniSlide traversing table connected to an AcuRite III digital counter with a precision of ± 0.001 mm. Crossdating was done visually while measuring the ring widths, using the output from the program RingRead. Average ring widths from each site were quite wide (Table 2.1) and no missing rings were evident.

Growth trends were removed from individual tree-ring chronologies using two different detrending methods: a cubic spline with a 50% frequency response cutoff at 50 years, and either a negative exponential or a straight line curve with the option of

Table 2.1. Parameters of the tree ring chronologies.

	SF	RL	BR	NL	PR
Number of radii	34	30	21	28	10
Number of trees	21	22	13	28	10
Interval (minimum of 5 radii)	1833 - 1989	1846 - 1989	1866 - 1989	1857 - 1992	1852 - 1992
Mean ring width (mm)	0.89	2.55	1.76	1.47	1.89
Standard deviation (mm)	0.48	1.16	0.92	0.72	0.76
Mean sensitivity*	.12	.12	.15	.12	.13
First order autocorrelation*	.62	.63	.78	.51	.44

* note: these parameters are for the spline detrended standard chronologies

negative or horizontal slopes. Standardized mean chronologies from each site were created using the ARSTAN subroutine within the ITRDBLIB program (Grissino-Mayer et al. 1992).

2.3.2 Climate - growth relations

The relations between ring widths and climate were examined through linear regression and response function analyses using the program PRECON (Fritts 1993). Pearson correlations were calculated between climate variables (the predictors) and ring-width chronologies (the predictand) using linear regression (Fritts 1976). The predictors used were the mean monthly temperature and total monthly precipitation for 17 months extending back from September of the growth year to April of the prior growth year. Climate data from Fort Smith, N.W.T. were used from the period 1922 - 1989. A problem with correlation analysis is that intercorrelations between monthly climate variables can lead to spurious correlations between climate and growth (Fritts 1976). Response function analysis reduces intercorrelations between the climate variables by regressing orthoganalized principal components of the climate data against the ring-width chronology (Fritts 1976, Briffa and Cook 1989). Significance of the response function results was determined using bootstrapped confidence intervals (Cook 1990). However, because the results of response function analyses are sensitive to the number of variables used (Blasing et al. 1984), interpretation of climate - growth relations was based on both the correlation and response function results.

2.3.3 Spruce budworm activity

Spruce budworm outbreaks were inferred using a combination of two methods. Rapid growth reductions in the white spruce chronologies were used to identify periods which might coincide with the beginning of spruce budworm outbreaks (cf. Morin et al. 1993). Growth reductions in the white spruce chronologies relative to the jack pine chronologies were used to confirm the possibility of an outbreak and to indicate the temporal duration of the outbreak (cf. Blais 1962, Swetnam et al. 1985). Jack pine is subject to defoliation by the jack pine budworm (*Choristeneura pinus* Freeman) (Volney 1988), but it was not observed in Alberta until 1985 (Moody and Cerezke 1986).

Rapid growth reductions were identified by calculating the percent growth change between the standardized ring widths in each year relative to the ring widths for the previous five years. A period was considered to exhibit a significant rapid growth reduction if the ring widths for three consecutive years decreased by 15% or more relative to the five previous years.

The duration of spruce budworm outbreaks was determined following the methods introduced by Blais (1962) and modified by Swetnam et al. (1985). The method assumes that, if white spruce and jack pine exhibit generally similar responses to climate, large differences in their growth patterns should only be due to disturbances such as spruce budworm activity. The white spruce chronologies were corrected to remove climatic signals by (1) rescaling the pine chronology so that it had the same standard deviation as the white spruce chronology, (2) creating a residual chronology by subtracting the mean of the rescaled chronology from the annual value of the rescaled chronology, and then (3) subtracting the residual chronology from the white spruce chronology (exact formulae in Swetman et al. (1985)). Swetnam and Lynch (1989) found that known western spruce budworm outbreaks were evidenced in *Pseudotsuga menziessii* indices that were corrected using *Pinus ponderosa* as periods when at least three growth rings were lower than the mean value of the index, and that at least one of these growth rings was less than the lower 80% confidence limit. Confidence limits were calculated assuming a normal distribution.

In this study I created corrected indices from the three white spruce indices using a jack pine chronology created from all of the jack pine cores collected from the Parsons Road (PR) and Ninisith Lake (NL) sites. This was done to maximize the regional climate signal present in the jack pine chronology. I note whether growth reductions in the corrected indices were greater than the 80% confidence limits Swetnam and Lynch (1989, 1993) found to be useful, or were greater than the 95% confidence limits typically used in statistical analyses.

2.3.4 Fire activity

The relations between ring-width patterns and fire activity were determined using two methods. First, Pearson correlation coefficients were determined between the mean value of the seven different fire weather variables (FWVs) over the entire fire season and the value of each of the five tree ring chronologies in the fire year (t) and the following year (t+1). The fire season in WBNP is between May 1 and August 31, the period during which 99% of the fires start (WBNP file).

The seven FWVs are the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC), the Drought Code (DC), the Initial Spread Index (ISI), the Build Up Index (BUI), the Fire Weather Index (FWI) and the Daily Severity Rating (DSR). The FWVs are constructed using daily meteorological observations of relative humidity, wind, temperature and precipitation (Van Wagner 1987). The FFMC indicates the dryness of the fuel as a result of drying at the scale of days, the DMC at the scale of weeks, and the DC at the scale of months. The ISI indicates the potental rate of spread of a fire, the BUI indicates the potental intensity of a fire, and the FWI and DSR (an exponential function of the FWI) combine the ISI and BUI to indicate general fre actvity. Records of the FWVs were available from Fort Smith NWT for the period 1957-89 (WBNP file).

Correlations between the FWVs and the ring width in the following year were determined because weather conditions in previous years can influence growth in following years through their effect on feed forward factors such as nutrient reserves and bud formation (Fritts 1976). As a result, the ring width in the following year might indicate climate conditions in the present year as well as might the actual growth in the present year.

Second, Spearman rank correlation coefficients were calculated between annual area burned (AAB) in WBNP and the ring width chronologies in the fire year (t) and the following year (t+1) for the period 1950 to 1989. Spearman rank correlations were used because AAB in WBNP is not normally distributed.

2.4 RESULTS

2.4.1 Tree ring chronologies

The spline detrended standard chronology from each of the five sites exhibited higher mean sensitivities, lower first order autocorrelations and had more variance explained by climate in response function analysis than did the chronologies created using the option of either negative exponential or horizontal detrending, or the ARSTAN chronologies created following autoregressive modelling. All further analyses therefore used the spline detrended standard chronologies (see Table 2.1).

The five tree ring chronologies exhibit similar short term variations in ring-widths (Fig. 2.2), although the amplitude of variation was higher for white spruce. The ring-width chronologies from the five sites were all significantly correlated (Table 2.2), but intra-specific correlations were higher than inter-specific correlations. The ring-width chronlogies exhibit no long term (centennial scale) trends in their raw form (Fig. 2.2) or following low pass filtering (not shown).

2.4.2 Climate - Growth Relations

The amount of variance explained by the climate response function model was highest for the white spruce site SF, intermediate for the two jack pine sites (PR and NL), and lowest for the white spruce sites RL and BR (Fig. 2.3). All five sites show a statistically significant positive reponse function or correlation coefficient with

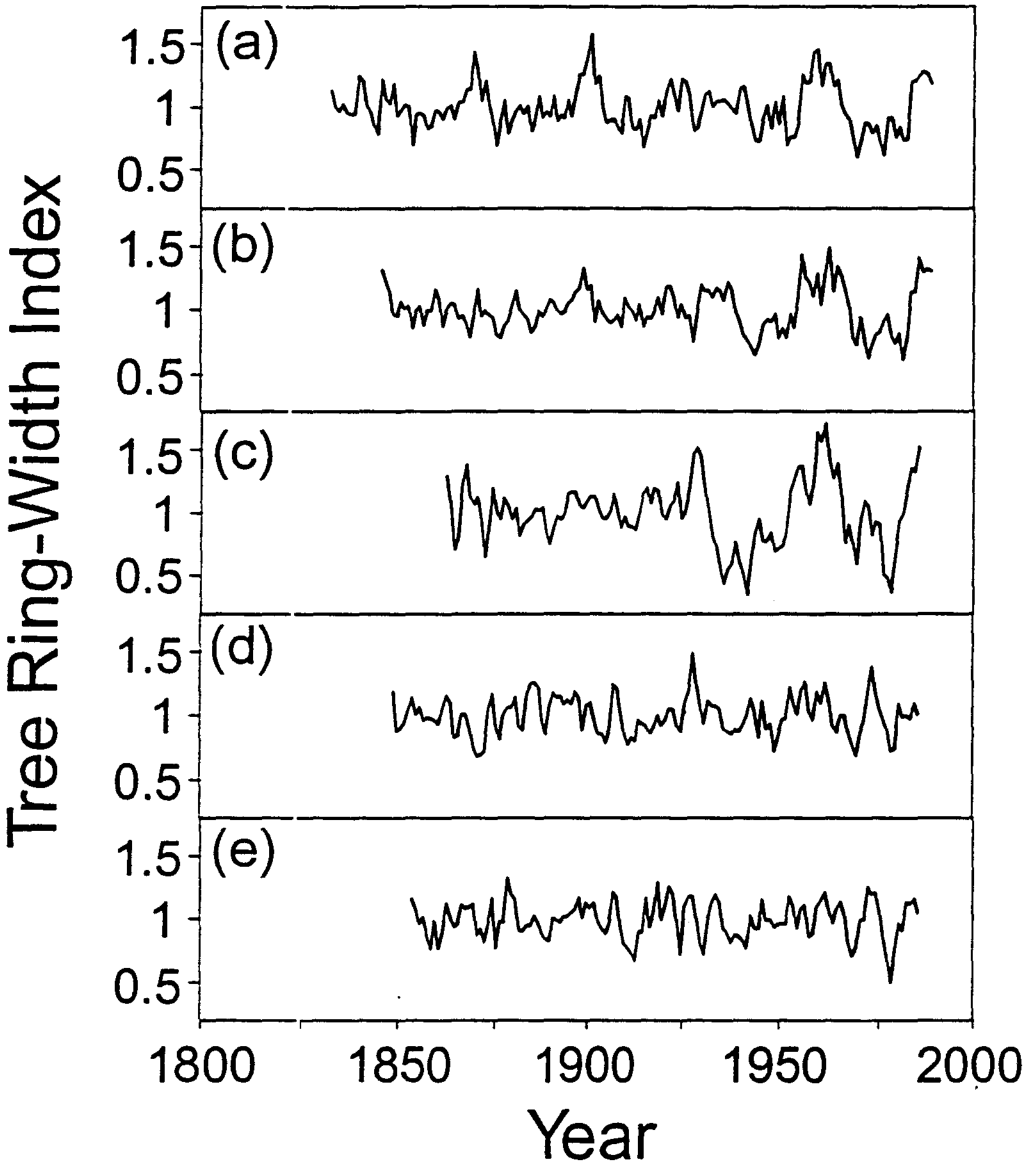

Figure 2.2. Spline detrended, standard tree ring chronologies from (a) Salt Flats (SF), (b) Rainbow Lake (RL), (c) Bad Road (BR), (d) Parsons Road (PR) and (e) Ninisith Lake(NL).

Table 2.2. Pearson correlations between ring width chronologies during the common interval 1866-1989 (n = 124). All correlations are significant at p < .001.

	SF	RL	BR	PR
RL	.69	-	-	-
BR	.55	.68	-	-
PR	.36	.47	.43	-
NL	.43	.46	.49	.62

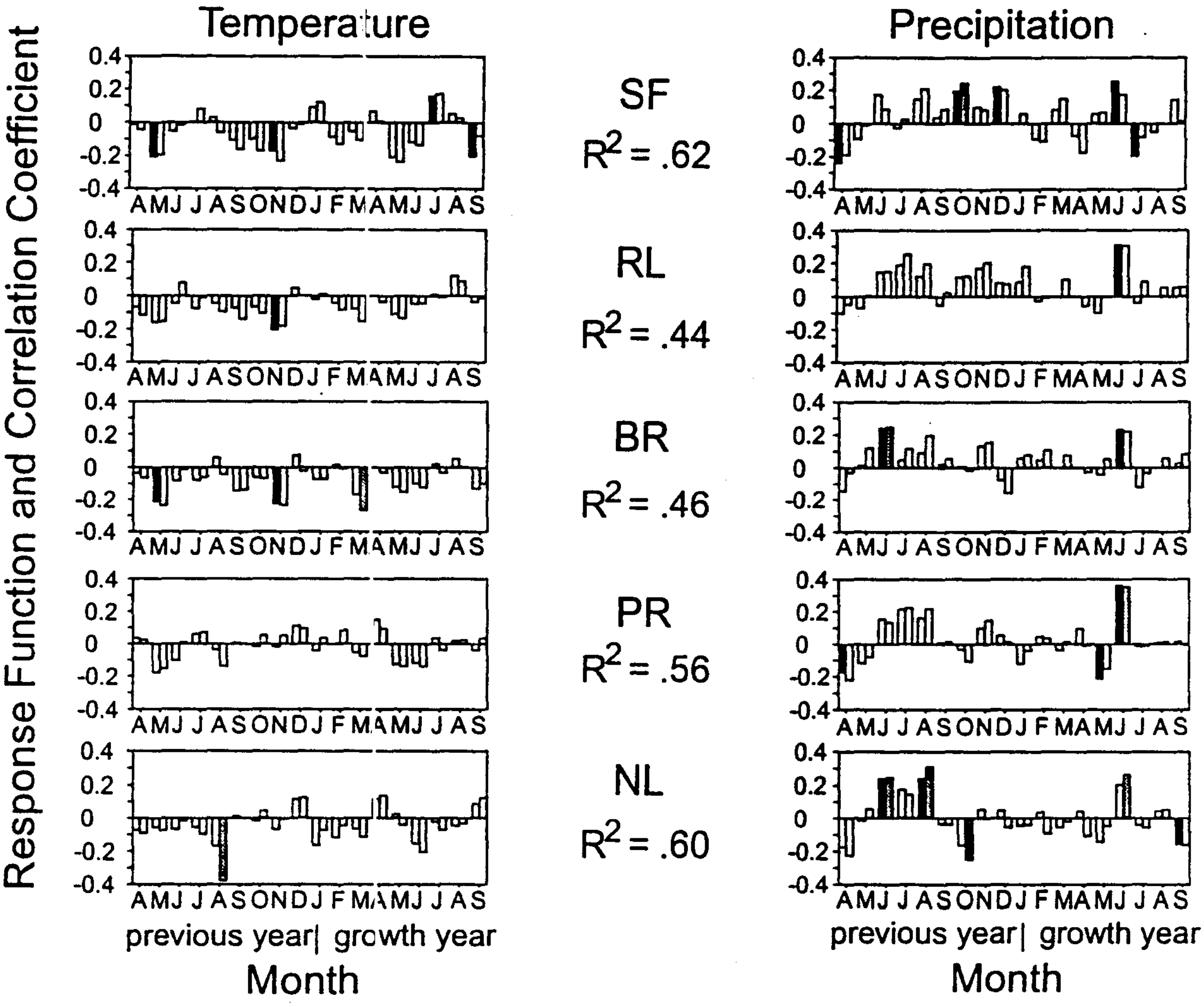

Figure 2.3. Response function and correlation coefficients for the 5 tree ring chronologies, using monthly climatic means (1922 - 1989) from Fort Smith, NWT. The pair of bars at each month show the response function coefficient (left) and the correlation coefficent (right). Black bars are response function coefficients significant at $p \leq .05$, and gray bars are Pearson correlation coefficients significant at $p \leq .05$. R^2 indicates the proportion of variance in the tree ring chronology between 1922 and 1989 that could be accounted for by monthly climate in the multiple regression model.

precipitation in June of the growth year. The BR white spruce and NL jack pine sites also show significant positive response function and correlation coefficients with June precipitation in the prior year. All three of the white spruce chronologies exhibited significant negative response function coefficients with November temperature in the prior growth year, and the SF and BR white spruce chronologies also exhibited significant negative response function coefficients with May temperature in the prior growth year.

2.4.3 Spruce budworm activity

Three periods in the three white spruce chronologies exhibited co-occurrence of significant rapid and relative growth reductions possibly indicative of spruce budworm outbreaks (Fig. 2.4, Table 2.3). The last inferred outbreak. between 1966 and 1971 at SF and between 1968 and 1970 at RL, is coincident with the extensive outbreak observed in WBNP by the FIDS between 1966 and 1971 (Fig. 2.1). The duration of the inferred spruce budworm outbreaks ranged from 3 to 13 years and averaged ~6 years.

2.4.4 Fire activity

Five of the seven fire weather variables (FWVs), (all but DC and FFMC), exhibited significant negative correlations with ring widths in the fire year from the BR white spruce chronology (Table 2.4). DSR, FWI and ISI were significantly negatively correlated with ring-widths in the fire year from all three of the white spruce chronologies. All seven of the FWVs exhibited significant negative correlations

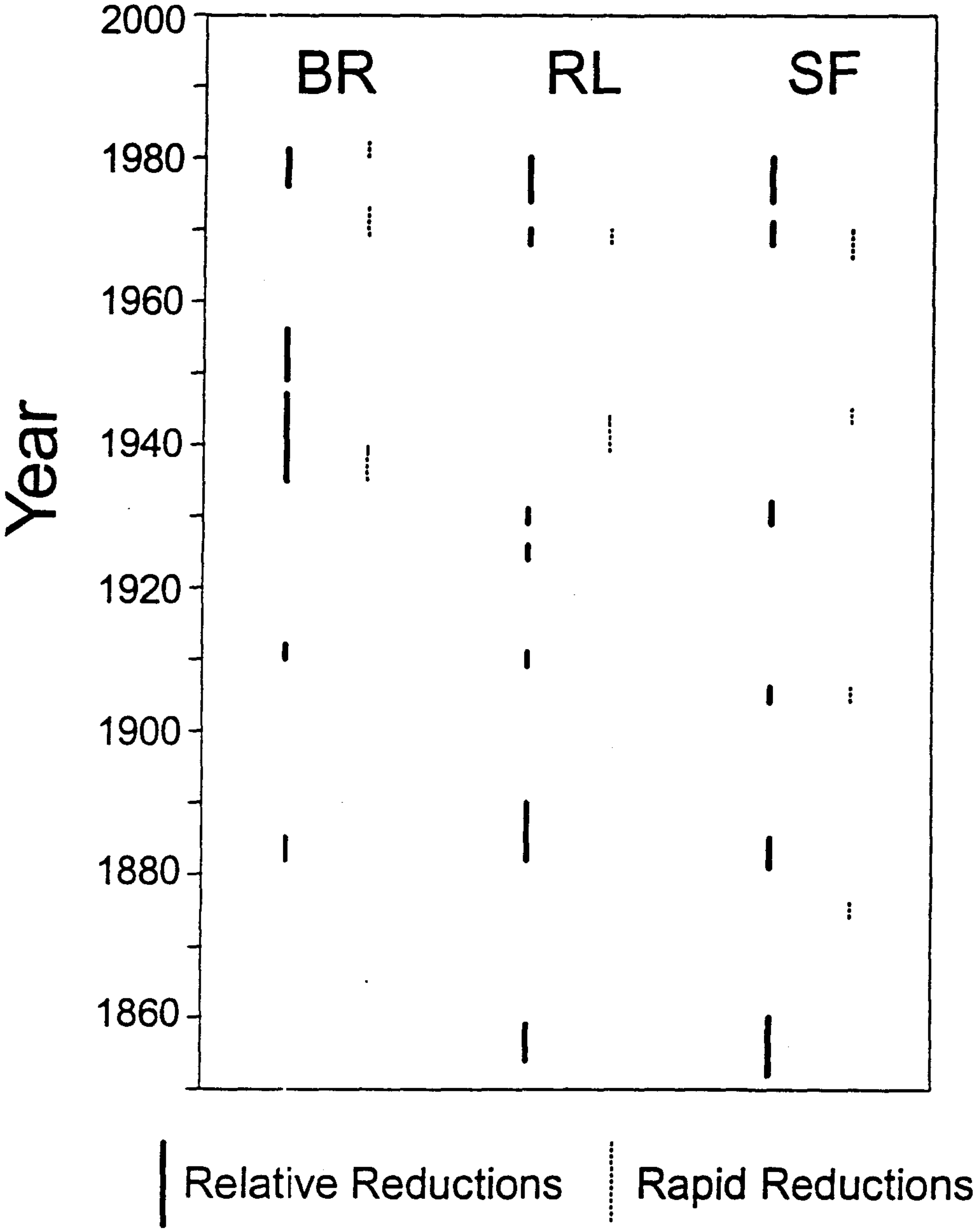

Figure 2.4. Periods during which the tree ring-width chronologies from BR, RL and SF exhibit significant relative growth reductions and significant rapid growth reductions that are possibly indicative of spruce budworm outbreaks.

Table 2.3. Periods when there are co-occurrences of rapid and relative growth reductions in the tree ring width chronologies. These reductions suggest spruce budworm outbreaks.

SF	RL	BR
1904 - 1906		
		1935 - 1947
1966 - 1971	1968 - 1970	

Table 2.4. Pearson correlations between the mean fire season (May 1 - August 31) values of fire weather variables (FWVs) in the fire year, and the tree ring-width chronologies from the fire year (n=33) and from the following year (n=32), 1957 - 1989.

FWV	Tree Ring-Width Chronology				
	SF	RL	BR	NL	PR
			FIRE YEAR (t)		
DSR	-.46**	-.43*	-.43*	-.34	-.15
FWI	-.43*	-.39*	-.41*	-.31	-.10
ISI	-.44*	-.44*	-.39*	-.29	-.16
BUI	-.37*	-.30	-.36*	-.30	-.08
DMC	-.33	-.28	-.35*	-.34	-.11
DC	-.28	-.19	-.23	.04	.07
FFMC	-.23	-.19	-.26	-.22	.02
			FOLLOWING YEAR (t+1)		
DSR	-.35	-.37*	-.61***	-.58***	-.42*
FWI	-.32	-.36*	-.60***	-.57***	-.38*
ISI	-.41*	-.42*	-.58***	-.52**	-.42*
BUI	-.22	-.28	-.54**	-.53**	-.32
DMC	-.17	-.23	-.48**	-.50**	-.28
DC	-.21	-.26	-.49**	-.42*	-.31
FFMC	-.15	-.22	-.47**	.50**	.28

* $p \leq .05$, ** $p \leq .01$, *** $p \leq .001$

DSR (Daily Severity Rating), FWI (Fire Weather Index), ISI (Initial Spread Index), BUI (Build Up Index), DMC (Duff Moisture Code), DC (Drought Code), FFMC (Fine Fuel Moisture Code) with ring-widths in the following year from the BR white spruce chronology and the NL jack pine chronology (Table 2.4). DSR was significantly negatively correlated with ring widths in the following year from the BR and RL white spruce, and the PR and NL jack pine chronologies; these correlations were the highest obtained between any of the FWVs and ring widths in either the fire year or the following year. ISI was significantly negatively correlated with ring widths in the following year.

All of the chronologies exhibited significant negative correlations between AAB and ring-widths in either the fire year or the following year (Table 2.5, Fig. 2.5). The highest correlation was with the BR white spruce ring-width value from the following year, the second highest correlation was with the BR chronology in the fire year, and the third highest correlation was with the NL jack pine ring-width value from the following year.

2.5 DISCUSSION

2.5.1 Climate - growth relations

The importance of precipitation in June of the growth year is probably related to this being the month in which growth ring formation begins (C.P.S. Larsen, pers. obs.) and that ring formation in upland forests in the WBNP area is limited by soil water availability. For white spruce, the positive correlation is likely limited to one month because high latitude populations can form annual rings within 45 days (Gregory and Wilson 1968). Since ring formation in mid-latitude jack pine populations occurs more quickly than it does in mid-latitude white spruce populations

Table 2.5. Spearman correlations between annual area burned in Wood Buffalo National Park (1950-1989) and the ring-width chronology values from the fire year (t) and the following year (t+1).

Site	t (n=40)	t+1 (n=39)
SF	-.38**	-.26
RL	-.34*	-.25
BR	-.50***	-.53***
NL	-.15	-.47**
PR	-.33*	-.46**

* $p \leq .05$, ** $p \leq .01$, *** $p \leq .001$

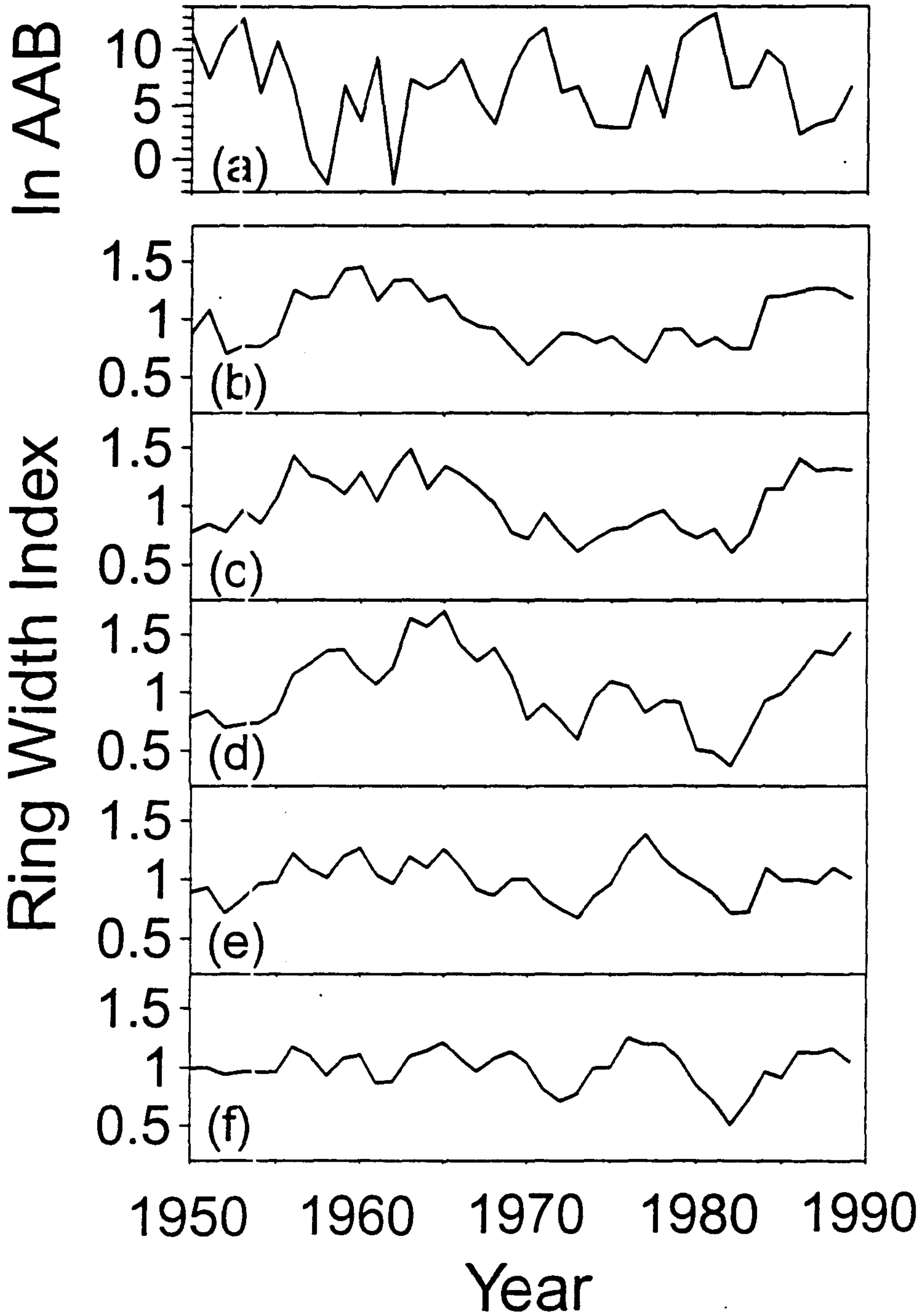

Figure 2.5. (a) The annual area burned in Wood Buffalo National Park, and the tree ring-width chronologies from(b) SF, (c) RL, (d) BR, (e) PR and (f) NL, for the period 1950 to 1989.

(Nienstaedt and Zasada 1990, Rudolph and Laidly 1990), it is expected that high latitude jack pine ring formation should also be rapid. The high correlations with precipitation in the summer prior to the growth season might be due to the positive effect this has on tree vigour and nutrient reserves for the following year. The negative correlation with prior May temperature exhibited by the white spruce may be related to moisture stress during the formation of buds which begins in May (Nienstaedt and Zasada 1990). It is unclear why white spruce exhibit negative correlations with prior November temperatures.

These results suggest that the ring-width chronologies, despite their low mean sensitivities and high autocorrelations (Table 2.1), should be able to provide useful proxy information of past climate variation in this area. The chronologies do not exhibit long term (centennial scale) growth trends but do show shorter term decadal scale variations in growth (Fig. 2.2). This lack of a long term trend was not due to the flexible spline detrending used (cf. Briffa et al. 1992), since long term trends were not apparent either in the chronologies created using the option of either negative exponential or straight line detrending. It is, however, likely that all standardizaton methods will remove centennial scale patterns from any chronology less than 400 years long. The brevity of the records obtained in WBNP therefore does not allow the observation of the centennial scale growth trends observed in longer ring-width chronologies from many treeline sites in northern Canada (Jacoby and D'Arrigo 1989). It is notable, though, that long term trends have not been observed in multi-century chronologies from the high boreal forest of western Canada

(Schweingruber et al. 1993), suggesting that changes in climate that are critical to tree growth may not have occurred at the centennial time scale in the western Canadian boreal forest.

2.5.2 Spruce budworm activity

The congruence between the observed spruce budworm outbreak between 1966 and 1971 (Fig. 2.1), and the inferrence of spruce budworm outbreaks in the SF and RL tree ring records (Fig. 2.4), suggests some validity to the approach of combining the relative (Swetnam and Lynch 1989) and rapid (Morin et al. 1993) growth reduction methods to infer spruce budworm outbreaks. However, given that only one known major spruce budworm outbreak has occurred in WBNP, and that it is not known whether this outbreak actually occurred in the tree ring sites used in this study, the validation of this method is not strong. As a result, the inferrence of spruce budworm outbreaks and the discussion of their potential effects on the interpretation of climate or fire from the tree-ring width chronologes is simply raised as speculation. Before the methods used in this analysis to infer spruce budworm outbreaks can be accepted, they must be validated in a location for which long permanent plot records of spruce budworm activity are available (eg. Swetnam and Lynch 1989).

A total of three spruce budworm outbreaks with an average length of ~6 years were inferred from the tree ring-width chronologies for the period between 1852 and 1989 (Table 2.3). The frequency of outbreaks in our study area is similar to that observed in nine study areas throughout Ontario, Quebec and New Brunswick, where between two and five outbreaks were observed between the beginning of the 19th century and latter part of the 20th century (Blais 1983). However, the 6 year average length of a spruce budworm outbreak in our study area is relatively short when compared to an average outbreak length of 18 years in southwestern Quebec (Morin et al. 1993), approximately 15 years in New Brunswick (Royama 1984) and approximately 11 years for western spruce budworm outbreaks in northern New Mexico (Swetnam and Lynch 1993).

It is notable that although the period between 1974 and 1980 exhibited the largest relative growth reduction observed at all three sites (Fig. 2.6), there were no concurent rapid growth reductions (Fig. 2.5) and, more importantly, only one spruce budworm observation was made in the study area during this period. It is unlikely that the FIDS could have missed such a long and severe spruce budworm outbreak (H. Cerezke per. comm.). There are many other time periods which exhibit significant relative growth reductions and no concurrent rapid growth reductions (Fig. 2.5). It is likely that these significant relative growth declines reflect differences in the climatic responses of the white spruce and jack pine. This is surprising given that two species had ring-width chronologies which were significantly correlated (Table 2.2) and only slightly different climate - growth relations (Fig. 2.3). These results therefore suggest that, although the relative growth reduction method has provided reliable records of spruce budworm activity in other studies (Swetnam and Lynch 1989, 1993, Eckstein et al. 1991), caution should still be used when applying the method.

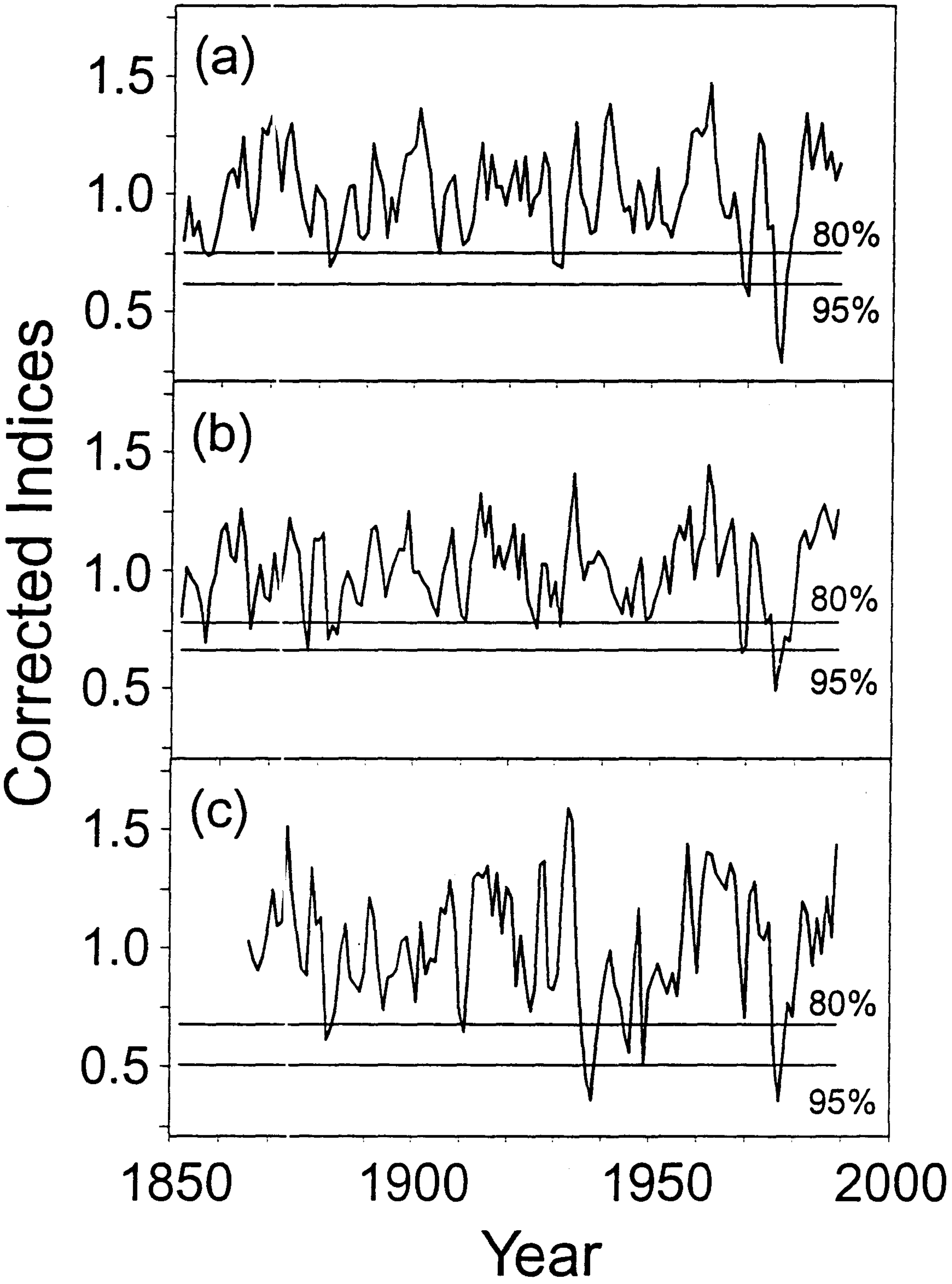

Figure 2.6. The corrected white spruce indices from (a) SF, (b) RL and (c) and BR..

If the inferred spruce budworm outbreaks could be accepted with some certainty, their occurrence could present some difficulty for the use of the white spruce tree- ring widths as proxy indicators of past climate. For example, although the white spruce chronologies are significantly correlated with climate, growth reductions due to spruce budworm activity could falsely be interpreted as extended periods of drought. It might be feasible to reconstruct climate using only those portions of the white spruce chronologies that do not exhibit spruce budworm outbreaks. However, it is possible that spruce budworm outbreaks might have occurred which were shorter than the minimum of three years that could be identified using our method. For example, the BR white spruce chronology exhibited a large, but statistically insignificant, one year relative growth reduction in 1969 that was likely due to the spruce budworm outbreak observed at SF, RL and much of our study area during this time (Fig. 2.1). These speculations, combined with the speculative nature of the inferred spruce budworm outbreaks in WBNP, underscore the caution recommended by Arquillière et al. (1991) when using chronologies from tree species host to insect defoliators as proxy records of short term climate variations.

2.5.3 Fire activity

The significant negative correlations between all of the ring-width chronologies, the FWVs and annual area burned (AAB) in either the fire year or the following year, suggests that these chronologies should provide useful records of both summer long fire weather and fire activity. These results therefore support the relations between ring widths, fire weather and fire activity found in Quebec (Archambault and Bergeron 1992, Bergeron and Archambault 1993). The FWV that exhibits the highest correlation with ring-widths, the DSR (Table 2.4), also has the highest correlation with AAB in WBNP (Chapter 3). That correlations are highest with the DSR is not unexpected given that it combines the other fire weather variables to reflect general fire activity (Van Wagner 1987). That ring width is also strongly correlated with DSR likely occurs because, although the FWVs have been parameterized to indicate the relative dryness of dead forest fuels (Van Wagner 1987), the component meteorological variables also affect tree physiology. For example, the warm, dry and windy conditions which enhance the activity of individual fires will also increase moisture stress in trees, resulting in declines in the total leaf chlorophyll and amount of wood production (Buxton et al. 1985).

It is intriguing that while significant correlations were obtained between ring-widths and the average weather during the May 1 to August 31 fire season (Table 2.4), the climate-growth analyses (Fig. 2.3) indicate that only June precipitation during the fire season was significantly correlated with ring width. This may occur because the monthly climate-growth analyses use simple monthly means of weather variables and treat each month of weather independently, while the FWVs employ daily weather conditions and integrate them through the whole fire season in a manner perhaps more similar to the way in which tree growth integrates seasonal weather. That ring-widths in the following year exhibit the highest correlations with the FWVs (Table 2.4) suggests that seasonal weather which affects area burned also has an impact on physiological properties such as bud formation and nutrient storage which can in turn affect radial growth in the following year.

The white spruce and jack pine ring-width chronologies both exhibit significant correlations with mean fire season fire weather and AAB, suggesting they should be useful for reconstructing fire weather and AAB in WBNP. However, the white spruce ring widths may exhibit additional variance related to spruce budworm outbreaks (Table 2.3). If the speculatively inferred spruce budworm outbreaks did occur, the reduced ring widths produced during spruce budworm outbreaks could falsely suggest years to have high fire activity. As such, some caution should be used when inferring short term changes in AAB from white spruce ring-widths. However, given that the inferred spruce budworm outbreaks only appear to affect short term (3-13 year) growth reductions, spruce budworm activity should not present severe problems for reconstructing long term changes in AAB from white spruce in this region.

CHAPTER 3

FIRE - CLIMATE DYNAMICS
IN NORTHERN ALBERTA SINCE 1850

3.1 INTRODUCTION

Dendrochonological fire histories from the boreal forest exhibit large annual and decadal variations in the area in different time since last fire (TSLF) age-classes (eg. Heinselman 1973, Rowe et al. 1974, Zackrisson 1977, Suffling et al. 1982, Foster 1983, Cogbill 1985, Payette et al. 1989, Bergeron and Archambault 1993, Dansereau and Bergeron 1993, Engelmark et al. 1994). These studies have typically suggested that these variations result from annual to decadal scale variations in fire-climate. Alternative reasons for the variations in age-structure are that they reflect temporal variations in the number of ignition events that start fires (cf. Flannigan and Wotton 1991), or that the study areas are simply too small to record more constant regional scale fire-climate dynamics (cf. Johnson and Van Wagner 1985). If large episodic variations in fire activity, and resulting age-structure patterns, are due to short-term shifts in climate, then documenting and understanding these variations have important implications for modelling boreal forest dynamics (Antonovski et al. 1992, Shugart and Smith 1992) and the role of boreal forests as sources and sinks of CO_2 (Auclair and Carter 1993, Oechel et al. 1993, Smith and Shugart 1993).

Covariance between fires and climate at the annual to decadal scale have been detected in fire-scar records from some coniferous forests which have low-intensity fire regimes (Clark 1990, Swetnam and Betancourt 1990, Swetnam 1993). In the boreal forest, the high-intensity fire regime precludes the preservation of long fire-scar records. Recent fires overburn stands originating from previous fires, limiting knowledge of area burned to the most recent fires as represented by the TSLF classes.

In this study I examine the fire-climate dynamics in the boreal forest of Wood Buffalo National Park (WBNP), Alberta between AD 1850 and 1989. I hypothesize that episodic variations in annual and semi-decadal area burned occur and are related to climatic variations. Historical records are used to reconstruct annual area burned from 1950 to 1989. I use life table methods to analyse TSLF age class data to reconstruct temporal variations in area burned in WBNP for the period prior to 1950. Life table analysis is also used to test the statistical significance of apparent episodic variations in annual area burned for the period 1850 to 1989. To determine if climate may have caused annual and semi-decadal variations in area burned, the annual records and semi-decadal life table estimates of area burned are statistically compared with instrumental climatic records for the period 1915 to 1989 and with tree ring-width evidence of climatic variations for the period 1850 to 1989.

3.2 STUDY AREA

WBNP is 44,870 km^2 in size and is located in the central boreal forest of Canada (Fig. 3.1). Fort Smith, N.W.T. (60° 00' N and 111° 55' W), located on the

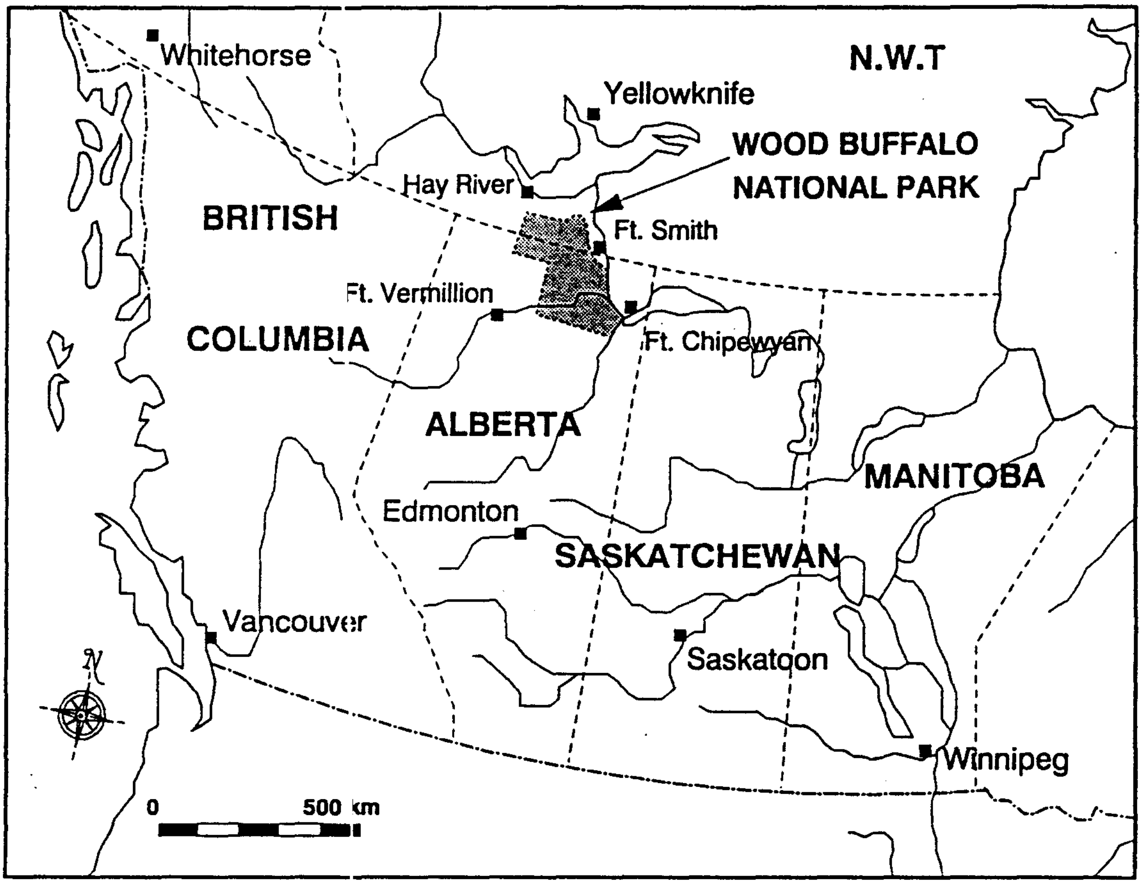

Figure 3.1. Location of Wood Buffalo National Park within western Canada.

northeastern edge of WBNP (Fig. 3.1), has a mean annual temperature of -3.3°C and a mean annual precipitation of 36.5 cm, with 21.9 cm falling as rain and 14.6 cm falling as snow (1951-1980 climate normals, Environment Canada 1982). July exhibits the highest mean monthly temperature (16.0 °C) and the highest mean total monthly precipitation (5.7 cm).

Topography in WBNP is flat to undulating, and rises from ~200 metres a.s.l. in the northeast to a maximum of ~1000 metres a.s.l. in the southwest. Forest covers 69% of WBNP, 24% is swamp and bog and 7% is water (Franklin 1993). Approximately 34% of the forest is dominated by black spruce (*Picea mariana* (Mill.)), 6% by white spruce (*Picea glauca* (Moench) Voss), 20% by jack pine (*Pinus banksiana* Lamb.), 24% by aspen (*Populus tremuloides* Michx.) and willow (*Salix* spp.), and 16% by mixed dominants (Franklin 1993).

Fire records have been kept in WBNP since 1950 (WBNP file). A total of 1011 fires occurred between 1950 and 1989, with 98% starting between May 1 and August 31. Annual area burned ranges from 0.001 km^2 in 1962 to 6519 km^2 in 1981 (Fig. 3.2). Fires larger than 10 km^2 make up only 8% of the fire occurrences, but cause 99% of the area burned. Fires ignited by humans account for 9% of the number of fires, and 11% of the area burned. Fire control has been ongoing within WBNP since the 1950s, although control actions are not taken on all fires. The vast size of the area burned in 1981 suggests that fire control may not have had a large impact on annual area burned.

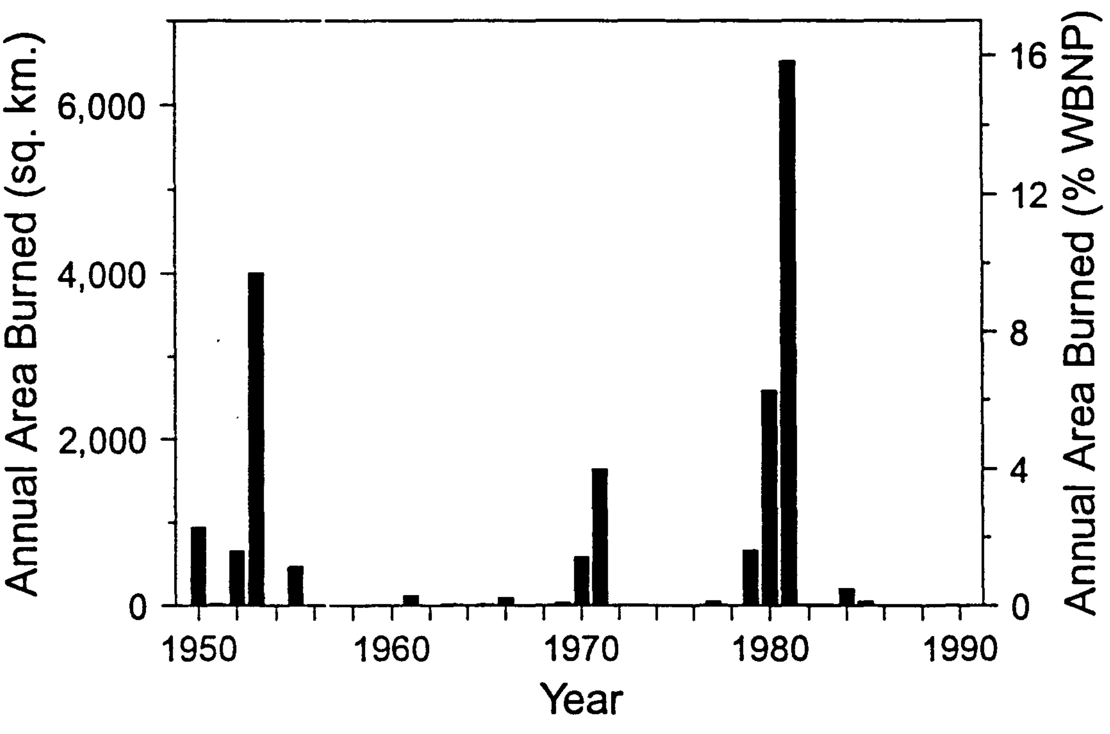

Figure 3.2. The annual area burned in Wood Buffalo National Park between 1950 and 1989.

3.3 METHODS

3.3.1 Fire history reconstruction

Records kept by the WBNP Warden Service (unpublished) provide data on annual area burned (AAB) for the period 1950 to 1989. Dendrochronological evidence is used to reconstruct semi-decadal variations in area burned for the period prior to 1950.

The time since last fire (TSLF) was determined for 166 stands distributed throughout WBNP (Fig. 3.3). WBNP was divided into 170 cells approximately 16 x 16 km in size. Four cells, located in flood dominated portions of the Peace-Athabasca delta, were subsequently excluded. Using random numbers, a sample point was located along roads that traversed 25 of the remaining 166 cells. Airphotographs covering 12 x 12 km were used to locate sample points in the other 141 cells. On the basis of random numbers, one photograph was chosen for each cell and a vegetated spot on that photograph was identified for sampling. When sample points were non-forested, the TSLF was determined for the nearest forest stand. A helicopter was used to visit the sites. When the forest was too dense for landing, sampling was done in a nearby stand that was connected to the original sample point by a contiguous forest with the same height and composition. This occurred infrequently because openings (eg. swamp, recent burn, rock outcrop) are common throughout WBNP. The exact location of the sampled sites was marked on 1:250 000 maps.

At each site, the TSLF was determined using a combination of the WBNP fire records, canopy tree-ages, and fire scars (Arno and Sneck 1977). The TSLF for most

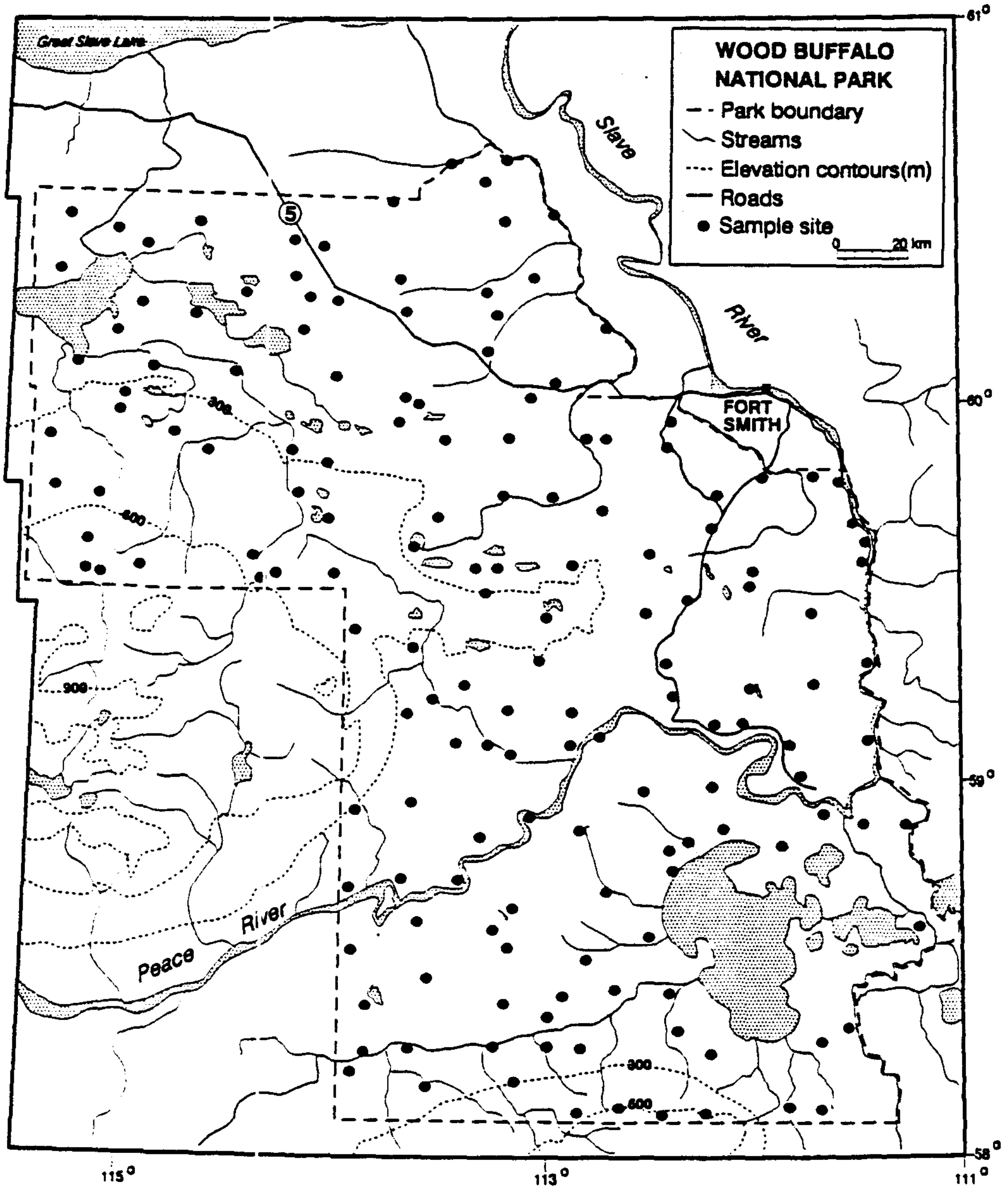

Figure 3.3. Location of the 166 time since last fire sample sites in Wood Buffalo National Park.

sites was estimated by aging disks collected from the base of between 3 and 10 canopy trees. Tree ages were typically clustered and the oldest age in the cluster was used to indicate the TSLF. If a site fell within the boundary of one of the burns identified on the 1950 - 1989 fire map, and either the boundary was visible from the air or the ages of the sampled seedlings or canopy tree were within five years of the mapped fire age, then the mapped fire age was used to indicate the TSLF.

Fire-scarred jack pine trees were present at some sites. Fire scars are formed when the heat of a fire kills part of the cambial growth layer under the bark of a tree (McBride 1983). Since annual growth rings will only be formed where the cambium survives, the number of growth rings between the bark and the scar indicates the TSLF. The most recent fire scar was used to indicate the TSLF for a site if stand-age data indicated that tree establishment closely followed the age of the last fire-scar, otherwise the oldest tree in the cluster of establishment ages was used to estimate TSLF. Disks were sanded and then annual rings were counted using a stereomicroscope.

To assess the accuracy of the TSLF estimates based on ages of canopy trees and saplings, relations between them and the TSLF based on fire-maps or fire-scars for 29 sites for which both data were available was examined using linear regression. The TSLF estimates based on tree ages are typically slightly lower than the actual TSLF (Fig. 3.4). The actual and estimated TSLF are significantly related ($r = .99$, $n = 29$, $p < .001$). The regression model is

$$\mathrm{TSLF}_{\mathrm{actual}} = 1.33 + 1.05\ (\mathrm{TSLF}_{\mathrm{est}}).$$

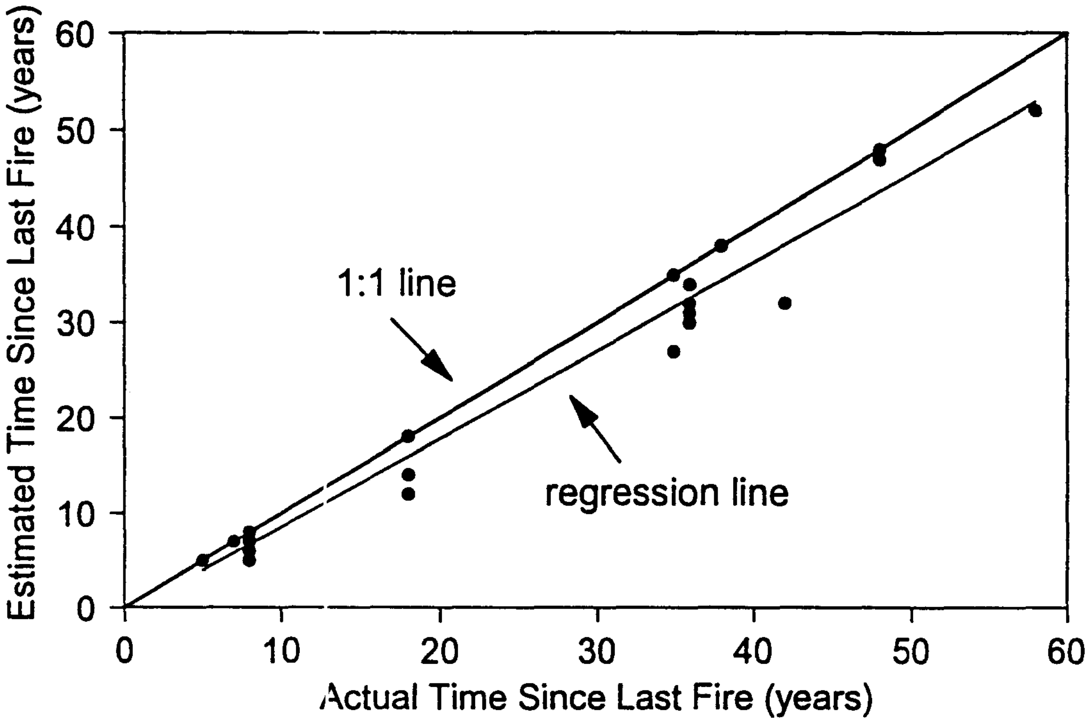

Figure 3.4. Relations between the actual time since last fire (based on fire maps and fire scars) and the time since last fire estimate based on tree ages.

the actual TSLF is on average only 5% older than the estimated TSLF and provide a reasonable approximation of TSLF for the purposes of this study. This bias probably occurs because, although most canopy trees become established in boreal forests within the first decade following a fire (Johnson and Fryer 1989, St-Pierre et al. 1992), random mortality of trees makes the chance of sampling a tree that established immediately following a fire more unlikely as time progresses (Fox 1989).

3.3.2 The life table approach

Life table methods can provide estimate of age and time specific mortality and survival rates using either cohort or age structure records (Southwood 1978). Cohort analysis involves following a birth cohort through time and recording the numbers still alive at different time intervals. The age specific mortality (hazard) rate for a cohort is then calculated as

$$h_x = \frac{2q_x}{b_x(1+p_x)}$$

where q_x is the conditional mortality (d_x/n_x) in an interval, d_x is the number dying in an interval, n_x is the number of individuals alive at the beginning of an interval, b_x is the width of the time interval, and p_x is the estimated proportion that survived the interval $(1 - q_x)$ (Fox 1993). The standard error of the hazard estimate $[SE(h_x)]$ is calculated as

$$SE(h_x) = \sqrt{\frac{h_x^2}{n_x q_x}\left[1 - \left(\frac{h_x b_x}{2}\right)^2\right]}$$

These methods can be applied to the population age structure, which represent the survival cohorts, if two assumptions are met (Krebs 1989): (1) the survival rate is the same for each age group, and (2) the same number of individuals are born into the population every year. In my case, the first assumption is probable given that most fire history distributions, including results from WBNP (Chapter 4), conform to a negative exponential model (eg. Bergeron 1991, Johnson and Larsen 1991) and this model suggests that survival is random. The second assumption is not relevant in our study since we hypothesize that there are temporal variatations in fire hazard. In most studies the second assumption is important because temporal variations in birth will change the effective size of the population, but since the population size in our study is constant at 166 stands, it is not a problem.

In my application of the life table method, temporal variations in fire hazard are estimated from the age structure of the WBNP forest landscape by defining d_x as the number of stands in the TSLF distribution in an age (time) class, and n_x as the number of TSLF stands which are in the time interval x and earlier time periods (ie. the number of TSLF stand of that age and older). This operationalization of the equation actually gives me the survival rate of a time class. Since I assume that variations in the survival rate are not due to variations in the subsequent hazard of being burned, but are due to variations in the number of stands initially formed at that time, this value should provide an estimate of the hazard of burning at that time.

The manner in which the life table method I employ provides meaningful results can be clarified by an example. Assume that TSLF ages are available for 1000 sample points in 10 year intervals. If exactly 10% of the sample points burned every 10 years, then 100 of the sample points would be in the most recent 10 year class, 90 sample points would be in the 10-19 year class (since 10% of the 100 sample points it contained when it was the 0-9 year class were burned in the most recent 10 years), 81 sample points would be in the 20-29 year class (since 10% of the 90 sample points it contained when it was the 10-19 year class would have been burned in the last 10 years), and so on. Using our life table method, the conditional mortality in the first class is 100/1000 = .1, in the second class it is 90/900 = .1, and in the third class it is 81//810 = .1. The fire hazard in each class is therefore the same and equal to .01 (ie. an average of 1% of the area is burned per year).

The TSLF data from WBNP were put into 5 year classes for life table analysis since the TSLF estimates are not accurate to the year. For each 5 year period the fire hazard, and the standard error of this estimate, were estimated using the SURVIVAL subroutine in SPSS (1988). The hazard of fire estimate and its standard error were multiplied by 100 so that they represent the estimated mean annual percent area burned (MAPAB) in WBNP in each five year period.

3.3.3 Fire-climate relations

Spearman rank correlations were calculated between the historical records of AAB in WBNP between 1950 and 1989 and the fire season (May 1 - August 30) means of temperature, precipitation and the Daily Severity Rating (DSR) fire behaviour variable. Instrumental records of temperature and precipitation were available from Ft. Smith (Fig. 2.1) for 1915 to 1989, and records of DSR was available for 1957 to 1989. The DSR incorporates the short and long term history of different weather variables (temperature, precipitation, relative humidity and wind), and is suggested to be a good overall measure of climatic conditions related to potential fire activity (Van Wagner 1987). Spearman correlations were calculated because AAB was not normally distributed.

Spearman rank correlations were calculated between the estimated MAPAB in each five year time period and five year non-overlapping means of temperature and precipitation during the fire season. Spearman correlations were used because the life table estimates of MAPAB between 1850 and 1989 are not normally distributed. Time-series of the five year non-overlapping means of temperature and precipitation from 1915 to 1989 were constructed from the instrumental records from Ft. Smith. The non-overlapping five year means of tree ring-widths were used to provide a proxy record of climate variation prior to 1915. Three white spruce indices and two jack pine indices are available from WBNP (Chapter 2). The longest index extends back to 1833 and the shortest index extends back to 1866. The ring-width indices from the fire year or the following year all exhibit significant negative correlations with the mean of DSR fromyera t or t+1 between 1957 and 1989 (r = .42 to .61; $p \leq .05$) and with AAB between 1950 and 1989 (r_s = .34 to .53; $p \leq .05$) (Chapter 2). Comparison of the non-overlapping five year means and five year binomial means from the tree-ring indices exhibited no evidence of aliased peaks or troughs (cf. Howarth and Rogers 1992).

3.4 RESULTS

Annual area burned (AAB) between 1950 and 1989 (Fig. 3.2) is significantly negatively correlated with mean fire season precipitation ($r_s = -.48$, $n = 40$, $p < .001$) and positively correlated with mean fire season temperature ($r_s = .27$, $n = 40$, $p < .05$). AAB between 1957 and 1989 is significantly negatively correlated with mean fire season DSR ($r_s = .68$, $n = 33$, $p < .001$).

The five year time since last fire (TSLF) classes (Fig. 3.5) exhibit a negative exponential distribution that reflects the overburning of older stands by more recent fires. The distribution also exhibits variations in class sizes that do not conform to a smooth negative exponential form, such as the low number of stands formed between 1925-1939 and 1955-1979.

There are large variations in the life table estimates of mean annual percent area burned (MAPAB) in the five year time periods (Fig. 3.6). Data prior to 1850 are not presented since there were insufficient samples (18 stands in 11 TSLF age classes) for the MAPAB estimates to be meaningful. The life table estimates of MAPAB for the period 1950 to 1989 are highly significantly correlated ($r_s = .95$, $n = 8$, $p < .001$) with the historical records of AAB grouped into five year, non-overlapping time classes. Interdecadal peaks in MAPAB occur in the periods 1850-4, 1890-4, 1920-4, 1950-4 and 1980-4. The average interval between peaks in MAPAB is roughly 30-40 years. The MAPAB estimates for high fire periods around 1920, 1950 and 1980, are

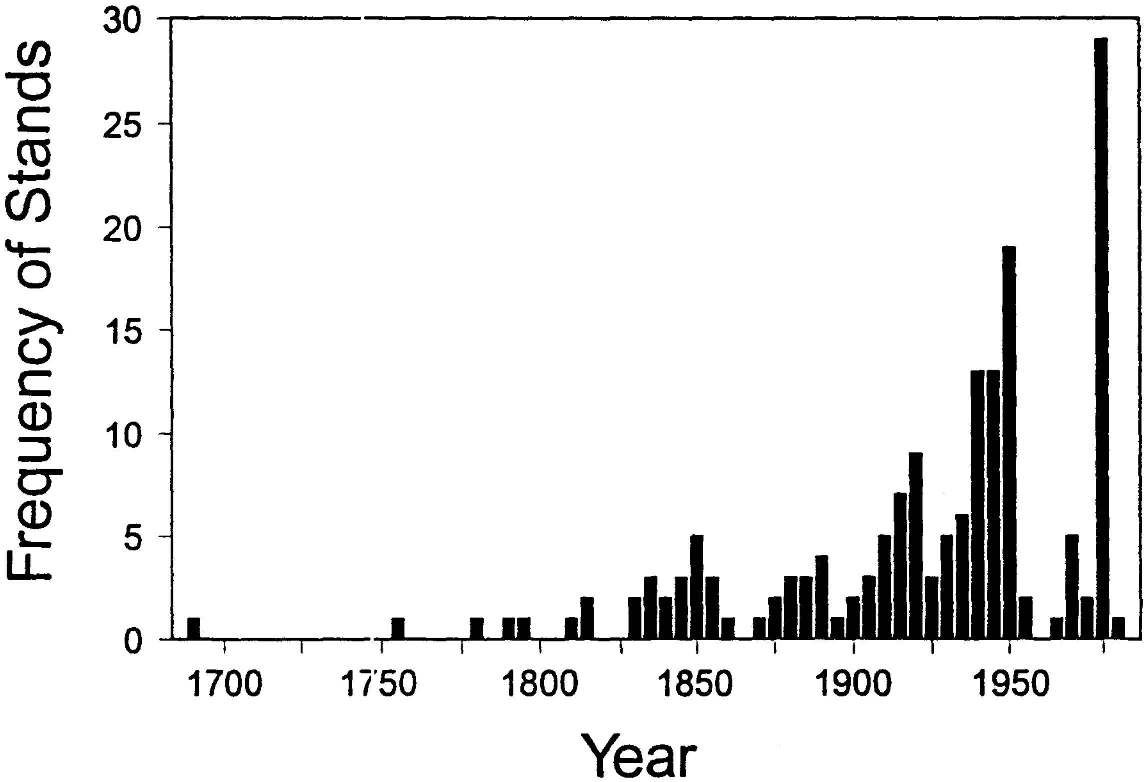

Figure 3.5. Frequency of time since last fire sites in five year time classes.

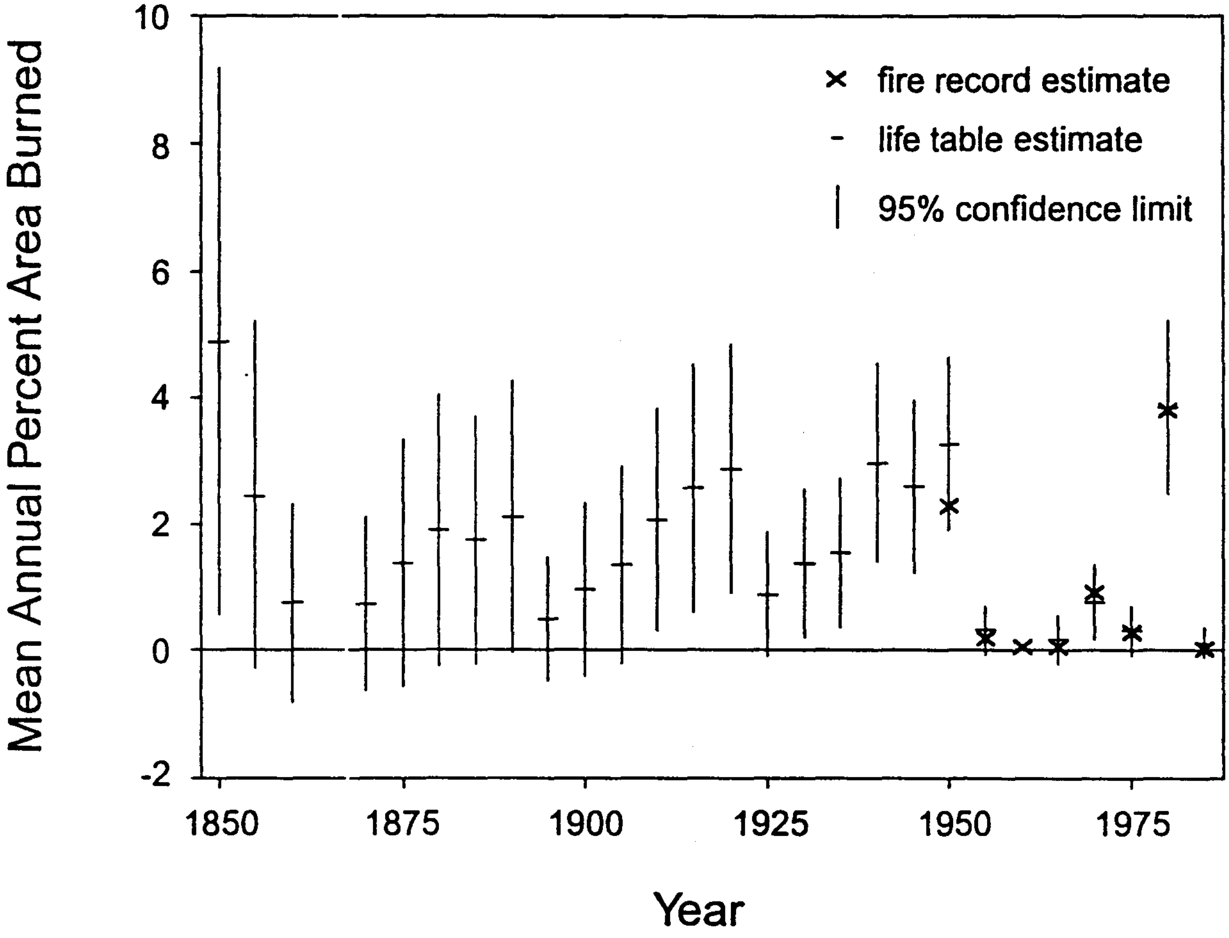

Figure 3.6. Life table based estimates of the mean annual percent area burned in Wood Buffalo National Park for five year time periods between 1850 and 1989, the 95% confidence limits of these estimates, and the mean annual percent area burned in the same five year time periods from historical fire records between 1950 and 1989.

significantly different from MAPAB estimates for periods with low fire activity as indicated by the 95% confidence limits presented on Fig. 3.6.

The MAPAB estimates between 1915 and 1989 are not significantly correlated with mean fire season precipitation (r_s = -.43, n = 15, p = .07), or temperature (r_s = -.08, n = 15). There are insufficient data points to statistically compare the MAPAB to the DSR for the period 1957 to 1989. However, tree ring-width indices are significantly correlated with DSR at the annual scale. MAPAB estimates for the period 1850 and 1989 are significantly negatively correlated with the three white spruce and two jack pine tree ring-with indices (Fig. 3.7, Table 3.1). The negative relationship between MAPAB and the tree-rings is consistent with the positive impact that high daily severity rating conditions would have on fire activity and negative impact such dry conditions would have on tree growth in this region (cf. Chapter 2).

3.5 DISCUSSION

3.5.1 The Life Table Approach to Estimating MAPAB

That my life table approach provides a meaningful reconstruction of semi-decadal variations in mean annual percent area burned (MAPAB) is clearly shown by the significant correlations with the historical fire records and the tree ring-width records (Table 3.1, Fig. 3.7). There are, however, some limitations with the method that should be recognized. Firstly, the time since last fire (TSLF) estimates in this study exhibit a bias with the actual TSLF being on average 5% older than the TSLF estimate. At 200 years this bias would be 10 years, and could lead to aliasing of the

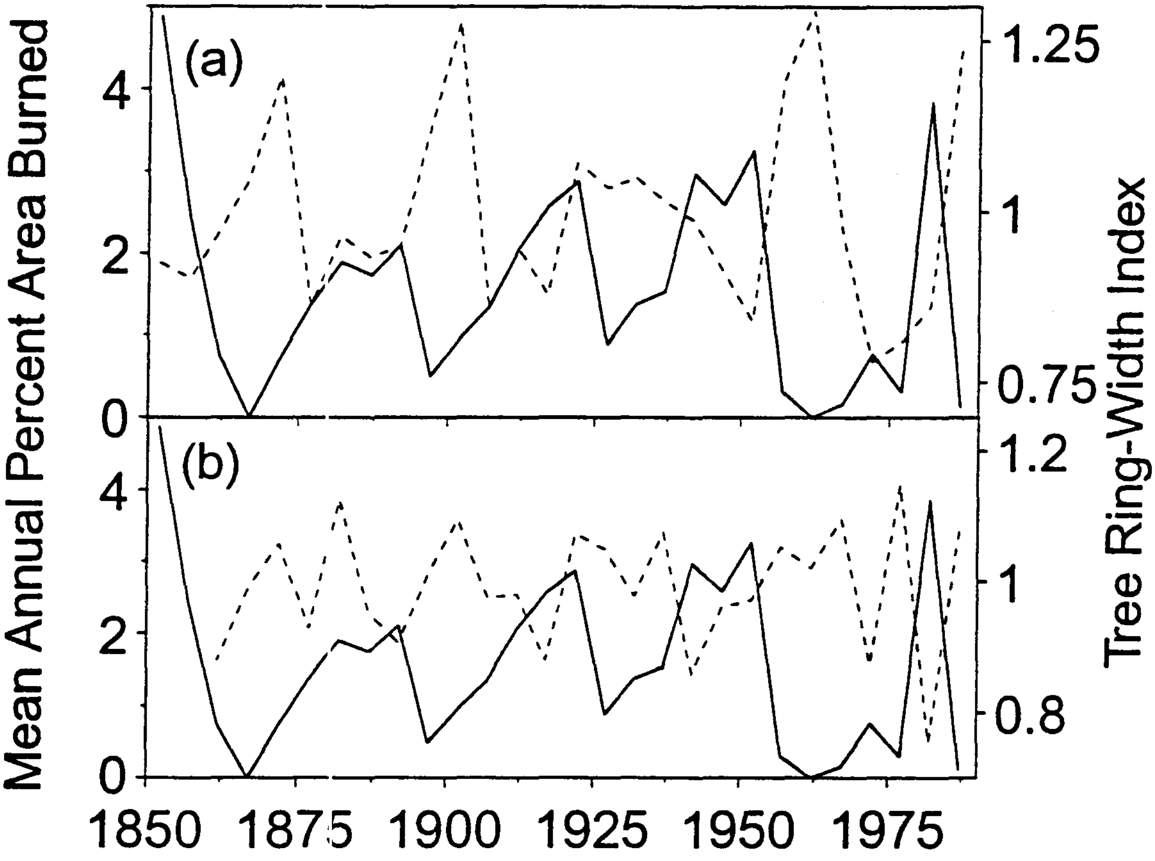

Figure 3.7. Life table based estimates of the mean annual percent area burned in Wood Buffalo National Park for five year time periods (solid line) and five year non-overlapping means (dotted line) of (a) the Salt Flats white spruce tree ring-width index, (b) the Ninisith Lake jack pine tree ring-width index.

Table 3.1. Spearman correlations between the life table estimates of mean percent annual area burned (MAPAB) in Wood Buffalo National Park (WBNP) and tree-ring width indices from 5 sites in WBNP. MAPAB and tree ring-width indices are non-overlapping five year means.

Tree ring-width index	Spearman correlation	Period (n)
Salt Flats[1]	$-.48^{**}$	1850 - 1989 (28)
Rainbow Lake[1]	$-.42^{*}$	1850 - 1989 (28)
Bad Road[1]	$-.68^{***}$	1870 - 1989 (24)
Ninisith Lake[2]	$-.49^{**}$	1860 - 1989 (26)
Parsons Road[2]	$-.34^{*}$	1855 - 1989 (27)

$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

[1] white spruce trees, [2] jack pine trees

MAPAB peaks. This bias could present a problem when correlating long term variations in MAPAB with tree ring-proxy records of climate.

A second limitation of the life table method is that, since estimates are grouped into 5 year classes, the measure of MAPAB will be less variable than individual measures of AAB. For example, during the 1950 to 1989 period, the peaks in MAPAB (Fig. 3.7) are much lower than are the peaks in annual area burned (AAB) (Fig. 3.2). The life table estimates therefore cannot provide information regarding whether peaks in MAPAB are the result of one large fire year or several moderate fire years. A third limitation of the life table method is that the 95% confidence limits are large and variations in MAPAB therefore cannot be interpreted without the aid of climate or proxy climate records. The confidence intervals would be smaller if more fire history sample sites were available but, because of the overburning of old stands, the sample size will always be small in the early part of dendrochronological fire history records.

3.5.2 Fire-Climate Relations in WBNP

The results of this study support the hypothesis that the area burned by wildfires in the boreal forest of WBNP varies at annual and semi-decadal scales in response to climatic variations. This is consistent with the variations in boreal forest age structure observed in other studies (eg. Heinselman 1973, Rowe et al. 1974, Zackrisson 1977, Suffling et al. 1982, Foster 1983, Cogbill 1985, Payette et al. 1989, Bergeron and Archembault 1993, Dansereau and Bergeron 1993, Engelmark et al.

1994). The correlations between AAB and instrumental temperature, precipitation and the Daily Severity Rating (DSR) records for the period 1950 to 1989, coupled with the correlation between MAPAB and DSR sensitive tree ring-width indices, support the contention that these episodic variations in area burned are related to climatic variations.

The increase in AAB with drier and warmer mean fire season conditions likely occurs because under these conditions there would be an increase in both the dryness and flammability of vegetation and in the amount of time for fires to burn. Similar fire-weather relations have been found at the monthly scale (Flannigan and Harrington 1988) and in non-boreal forests (Swetnam and Betancourt 1990, Balling et al. 1992).

It is surprising that while MAPAB at the semi-decadal scale is significantly negatively correlated with the 5 tree ring-width indices, it is not significantly correlated with mean fire season precipitation or temperature. This discrepancy is not the result of the different time spans over which the variables are correlated, since all of the tree ring-width indices other than RL exhibit significant negative Spearman correlations with MAPAB ($p < .02$) over the 1915-1989 period (results not shown). The better performance of tree ring-widths is likely related to tree growth and fire behaviour both responding to summer dryness in a similar manner, and possibly because they are both affected by dryness in seasons prior to the fire season. That tree ring-width indices exhibit significant correlations with MAPAB is encouraging for fire-climate research, since multi-century tree ring records that appear sensitive to climate are available for many areas (eg. Fritts 1991).

The occurrence of episodic variations in average temperature, precipitation and atmospheric pressure at annual to centennial scales have been identified in many studies (eg. Karl and Riebsame 1984, Knox et al. 1988, Trenberth 1990, Ghil and Vautard 1991). These changes in climate have been suggested to be the result of factors such as internal atmospheric dynamics, coupled atmosphere-ocean dynamics, volcanic eruptions and solar variability (reviewed in Crowley and Kim 1993, Rind and Overpeck 1993). The first two causes typically lead to changes in the average atmospheric flow patterns which will affect regional climatic changes, while the latter two causes can lead to hemispheric and global climate changes. Indeed, variations in AAB over a 35 year period in the southern Canadian Rockies (Johnson and Wowchuk 1993) and over an 86 year period in the southwestern United States (Swetnam and Betancourt 1990) have been related to coupled atmosphere-ocean dynamics, and there is some evidence that the variations in AAB over the Northern hemisphere are related to solar variability (Auclair and Carter 1993). Further research is required to determine what factors control the 30-40 year episodic variations in climate that drive AAB and MAPAB in WBNP.

CHAPTER FOUR

FIRE FREQUENCY VARIATIONS WITH FOREST DOMINANT, WATERBREAK PROXIMITY AND TIME IN THE BOREAL FOREST OF NORTHERN ALBERTA

4.1 INTRODUCTION

It has been suggested that fire frequency, defined as the mean annual probability of a site burning (Johnson and Van Wagner 1985), in the boreal forest can vary spatially in response to changes in vegetation and topography (eg. Zackrisson 1977, Johnson 1979, Yarie 1981) and temporally in response to changes in climate (eg. Bergeron 1991, Engelmark et al. 1994). Changes in vegetation and topography may affect the rate of fire spread (Van Wagner 1988, Forestry Canada 1992), while changes in climate may affect fire frequency by creating more extreme fire conditions or by providing more time for fires to burn (Flannigan and Harrington 1988, Renkin and Despain 1992). Since variations in fire frequency might affect terrestrial and aquatic ecosystem dynamics (eg. Bendell 1974, Bayley et al. 1992), and is a key concern for resource management (eg. Martell 1983, Reed and Errico 1986), knowledge of the average expected fire frequency in different areas and time periods is important.

An understanding of whether fire frequency has varied over space and time within a region can be developed by analyzing its fire history (Johnson and Van

Wagner 1985). The fire history can be reconstructed by determining the time since last fire (TSLF) from stands throughout the region by using fire records, fire scars and tree establishment ages. The TSLF is determined for a random sample of stands throughout the region (eg. Yarie 1981, Bergeron 1991) and if sampling is sufficiently dense the TSLF can be mapped for the entire area (eg. Heinselman 1973, Johnson and Larsen 1991). The TSLF estimates can be plotted as a survival distribution, and estimates of fire frequency can be obtained from it using a combination of graphical and statistical methods (Johnson and Van Wagner 1985). If the survival distribution exhibits breaks in its slope, then it may be composed of more than one surivival distribution. Such mixed survival distributions may arise from spatial and/or temporal variations in factors which control fire.

Spatial variations in boreal forest fire frequency have been purported in many studies. For example, it has been suggested that pine and aspen forests burn more than spruce forests (eg. Zackrisson 1977, Romme and Knight 1981, Yarie 1981, Cogbill 1985), dry sites burn more than more mesic sites (eg. Zackrisson 1977, Suffling et al. 1982, Clark 1990), and that fire frequency decreases with increases in topographic variation and the number of waterbodies (eg. Quirk and Sykes 1971, Heinselman 1973, Johnson 1979, Foster 1983, Bergeron 1991). These suggestions, however, were typically based on either informal observations (eg. Quirk and Sykes 1971, Heinselman 1973, Romme and Knight 1981, Foster 1983), or a non-statistical comparison of mean ages of stands (eg. Zackrisson 1977, Johnson 1979, Yarie 1981, Suffling et al. 1982, Cogbill 1985, Bergeron 1991).

The statistical methods of survival analysis, commonly used in ecology to estimate the survival rates of different populations and to evaluate whether these rates are different (eg. Harper 1977, Fox 1993), have recently been introduced to fire history (eg. Clark 1989). These methods involve either parametric or non-parametric regression of the survivorship curve on environmental covariates. The regression models do not require the data to be normally distributed and, since fire history data typically conform to an exponential or Weibull distribution (eg. Yarie 1981, Clark 1990, Johnson and Larsen 1991), these models should therefore be useful for testing whether fire frequency varies spatially. Using survival models Clark (1990) determined that fire frequency in northwestern Minnesota was significantly related to slope aspect but not to slope steepness, while Johnson et al. (1990) and Johnson and Larsen (1991) found that fire frequency in the southern Canadian Rockies did not vary spatially.

In the case where the mixed TSLF distributions could not be explained by spatial variations in fire frequency (Johnson et al. 1990, Johnson and Larsen 1991), they were suggested to be related to temporal changes in climate. Other studies have inferred temporal changes in fire frequency directly from the mixed TSLF distributions (eg. Bergeron 1991, Engelmark et al. 1994). These studies have all found that fire frequency has been significantly slower over the past 100-200 years than it was in the previous 100-200 years.

In this paper the fire history of the boreal forest of Wood Buffalo National Park is reconstructed and examined for spatial and temporal variations in fire frequency over the past 300 years. Previous fire history analyses from WBNP for the period between 1850 and 1989 found decadal scale variations in fire hazard that occurred in response to episodic changes in climate (Chapter 3). In this research I test whether fire frequency is higher in pine and aspen forests than it is in black or white spruce forests, and whether differences in the proximity of water breaks can explain the differences in fire frequency. I also examine whether average fire frequency at the centennial scale has changed over the past 300 years. Spatial variations in fire frequency are assessed using survival analysis methods, and temporal variations are assessed using logarithmic regression.

4.2 STUDY AREA

Wood Buffalo National Park (WBNP), 44,870 km^2 in size, is located in the central boreal forest of Canada (Fig. 3.1). WBNP is underlain by Palaeozoic deposits, dominated by limestone and gypsum, with outcrops of Precambrian granites along the Slave River (Airphoto Analysis Associates 1979). Glacial tills overlie the bedrock throughout most of WBNP. The tills are covered by a variable thickness of glaciolacustrine clays, silts and sands left by Glacial Lake McConnell (Airphoto Analysis Associates 1979). Sand dunes, now inactive, are present in many parts of WBNP as a result of post-glacial aeolian activity. Topography in WBNP is generally flat to undulating, and rises gradually from 200 metres a.s.l. in the northeast to a maximum of 1000 metres a.s.l. in the southwest along the margins of the Birch Hills and Caribou Mountains.

The climate, vegetation and fire patterns in WBNP have been described in section 3.2.

4.3 METHODS

4.3.1 Fire history reconstruction

The identifcation of 166 fire history sample points throughout WBNP, and the manner in which the time since last fire (TSLF) for each site was determined, has been described in section 3.3. The dominant tree species at each site was assessed qualitatively and recorded while in the field. The effect of waterbreaks on fire frequency was assessed by measuring the distance from sample points to the nearest waterbody (lake, river or stream) in each of the eight cardinal directions. Measurements were made using the 1:250 000 National Topographic Survey maps on which the sample sites were marked. The mean of the eight waterbreak distances (MWD) was calculated and used in the further analyses. The MWD is similar to the vector dispersion measure of topographic roughness used by Johnson (1979) to examine the affect of topography on fire frequency.

4.3.2 Fire frequency estimation

The TSLF estimates were put in 10 year classes and the cumulative TSLF survival distribution was plotted on semi-logarithmic paper. Ten year classes were used to dampen decadal scale variations in fire frequency that occur in response to short term climate changes (Chapter 3). The survival distribution was examined for changes in the slope indicative of a mixed distribution.

Accelerated hazard survival models were used to determine whether the survival distributions of different vegetation and mean distance to waterbreak classes were significantly different. These models parametrically regress survival on covariates (Lawless 1982, Clark 1990, Fox 1993). The model is

$$y = X\beta + \sigma\epsilon$$

where y is the natural logarithm of the survival age, X is a matrix of covariates, β is a vector of regression parameters, σ is a scale parameter and ϵ is a vector of error terms.

In this study survival was the TSLF, the covariates were vegetation types and mean distance to waterbreaks, and survival was modelled as an exponential distribution. Note that under an exponential distribution the scale parameter σ is set to one. TSLF distributions have been fit to both exponential and Weibull distributions (Johnson 1979, Yarie 1981, Bergeron 1991, Johnson and Larsen 1991), but in this study *post hoc* likelihood ratio tests (Lawless 1982) found that the Weibull distributions did not provide a significantly better fit. The accelerated hazards models were fit using the SAS (1985) program LIFEREG.

The accelerated hazards model provides a maximum likelihood estimate of survival for each covariate or classes of a covariate (Lawless 1982, Fox 1993). A chi-squared test evaluates whether the survival estimates of the different covariates or classes of a covariate are signficantly different. In this study, models of survival using vegetation classes and the MWD as covariates were made seperately, and then in combination to determine their relative importance. In the case of an exponential distribution, the regression parameter provides the survival estimate and it is equal to the mean of the distribution (Lawless 1982). The mean of the exponential distribution is equal to the fire cycle, which is the time required to burn an area equal in size to the entire study area (Johnson and Van Wagner 1985). Given an exponential distribution, the fire cycle is equal to the average interval between fires, which is the inverse of fire frequency (Johnson and Van Wagner 1985). Covariation between vegetation types and the MWD was assessed using the Kruskal-Wallis test (Neave and Worthington 1988).

An estimate of the average interval between fires in the jack pine sites was also made as the mean of the number of years between tree establishment and the first fire scar, and the mean number of year between consecutive fire scars. If survival is exponentially distributed, the average interval between fires and the fire cycle estimate from the jack pine survival distribution should be the same (Johnson and Van Wagner 1985).

Survival distributions were plotted for the sites with different vegetation dominants and MWD classes, and then examined for breaks in the slope indicative of changes in fire frequency. If different survival distributions exhibited breaks in their slope at the same time, it was inferred that the change in survival reflected temporal variations in fire frequency. The fire cycle in the different time periods was estimated through regression of the natural logarithm *(ln)* of the survival distribution. The slope of the regression curve is equal to the fire frequency (cf. Bergeron 1991), and its inverse is equal to the fire cycle. To determine whether the fire frequency estimates in the different time periods were significantly different, the slope coefficients from the regression analyses were compared using a *t*-test.

4.4 RESULTS

The location and dominant vegetation of the 166 time since last fire (TSLF) sample sites are shown in Fig. 4.1. The most frequent dominant is black spruce (39%), followed by jack pine (21%), white spruce (18%) and aspen (11%), with another 11% dominated by larch, birch or willow. These relative proportions are very similar to the 34% black spruce, 20% jack pine, 6% white spruce, 24% aspen and willow and 16% mixed dominants in Wood Buffalo National Park (WBNP) estimated by remote sensing (Franklin 1993), suggesting that the 166 TSLF samples provide a good representation of WBNP. The TSLF age classes are distributed throughout WBNP (Fig. 4.2), with the oldest age classes perhaps more frequent on the western side. The survival distribution for WBNP (Fig. 4.3) exhibits a change in slope indicative of a mixed distribution (ie. is a mix of two or more populations which have different fire frequencies).

The accelerated hazards model suggest that the fire cycles in the aspen and jack pine sites are significantly faster than in the black and white spruce forests (Table 4.1). Survival is significantly related to the mean waterbreak distance (MWD) ($p \leq .001$). When the TSLF data are classed by MWD (Table 4.2), the near and far MWD classes are significantly different ($p \leq .05$). Vegetation types exhibit significant

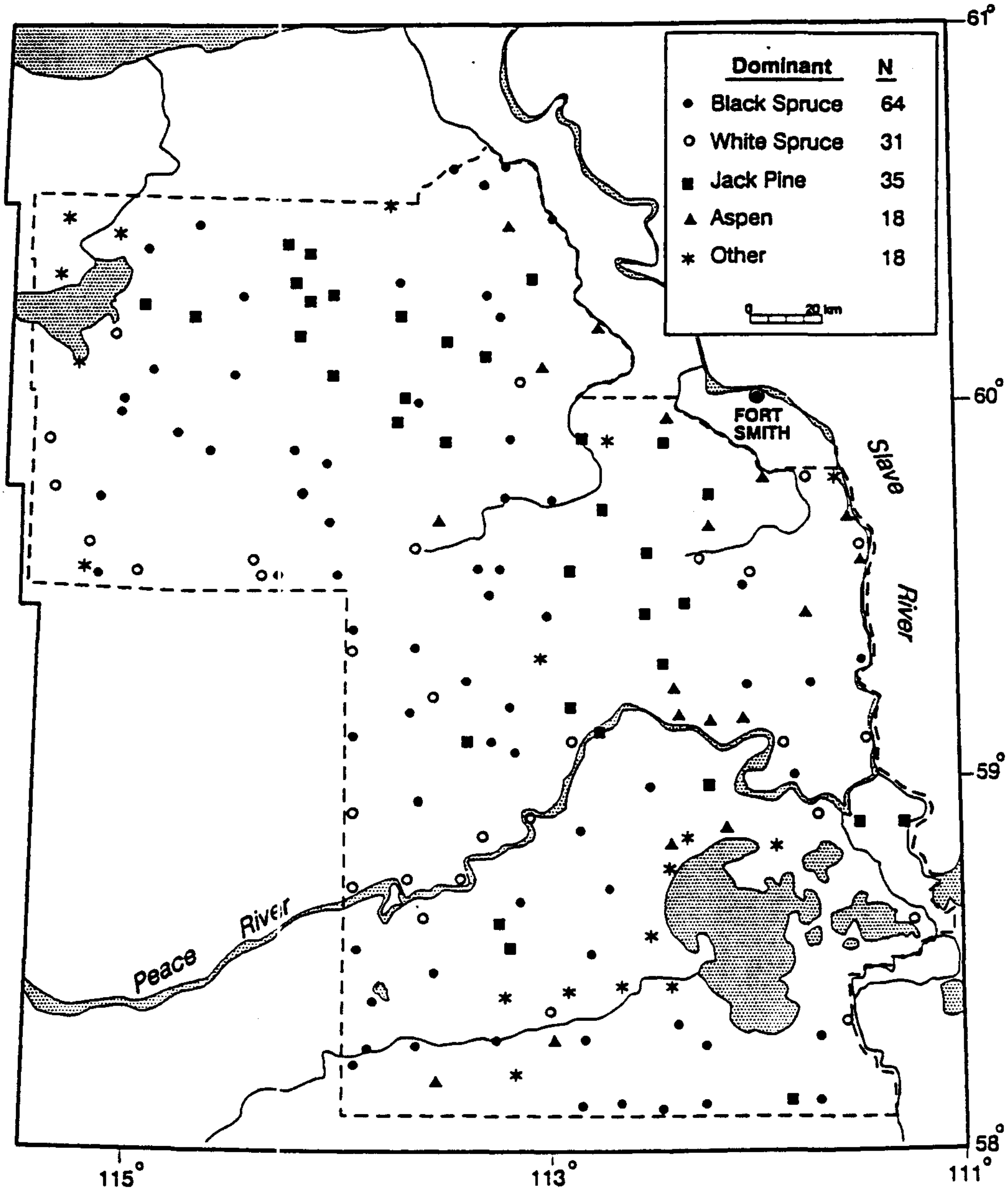

Figure 4.1. Location of the 166 time since last fire sample points within Wood Buffalo National Park, and the dominant vegetation at each sample point.

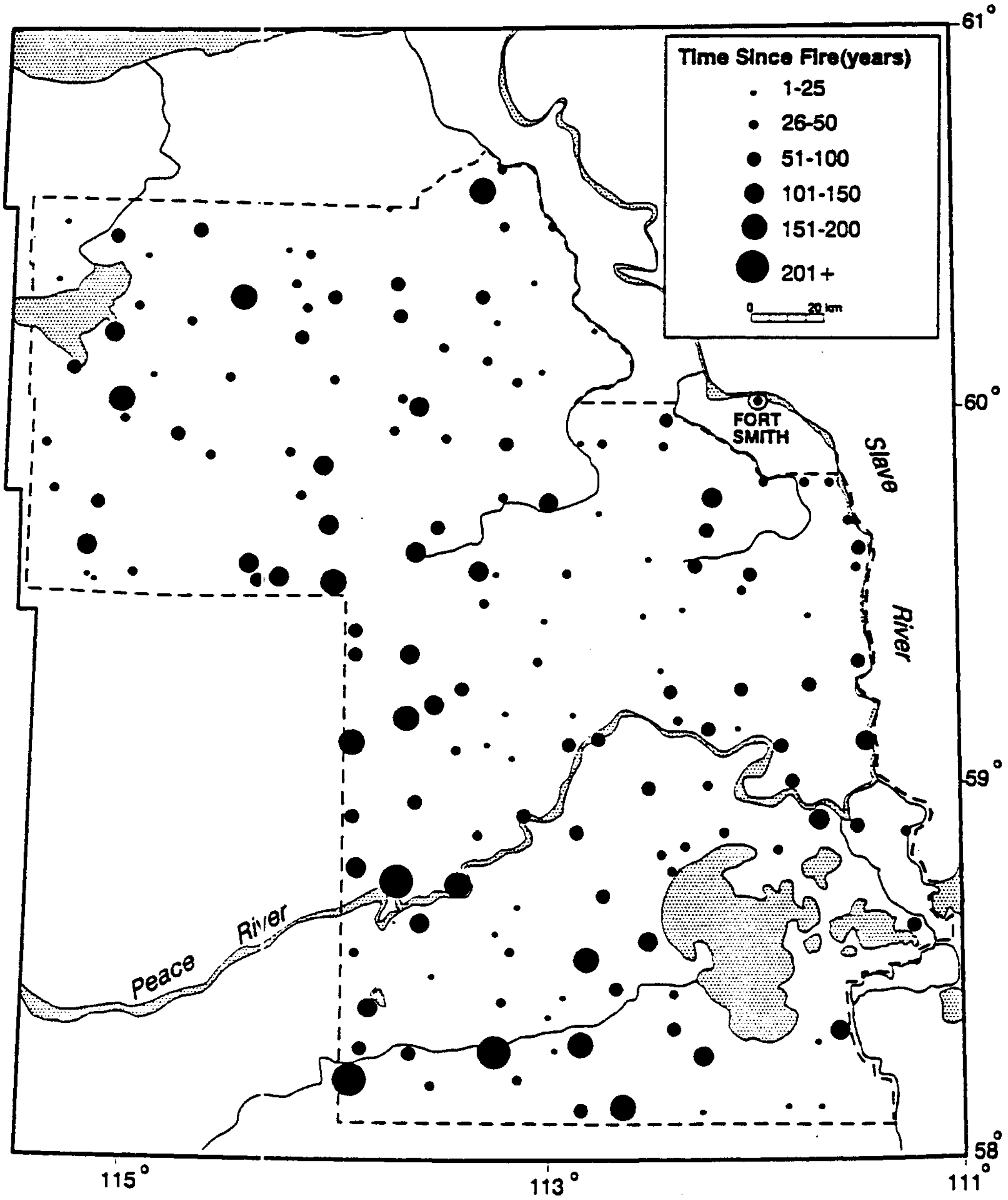

Figure 4.2. The time since last fire at each of the 166 sample points in Wood Buffalo National Park in 25 and 50 year age classes.

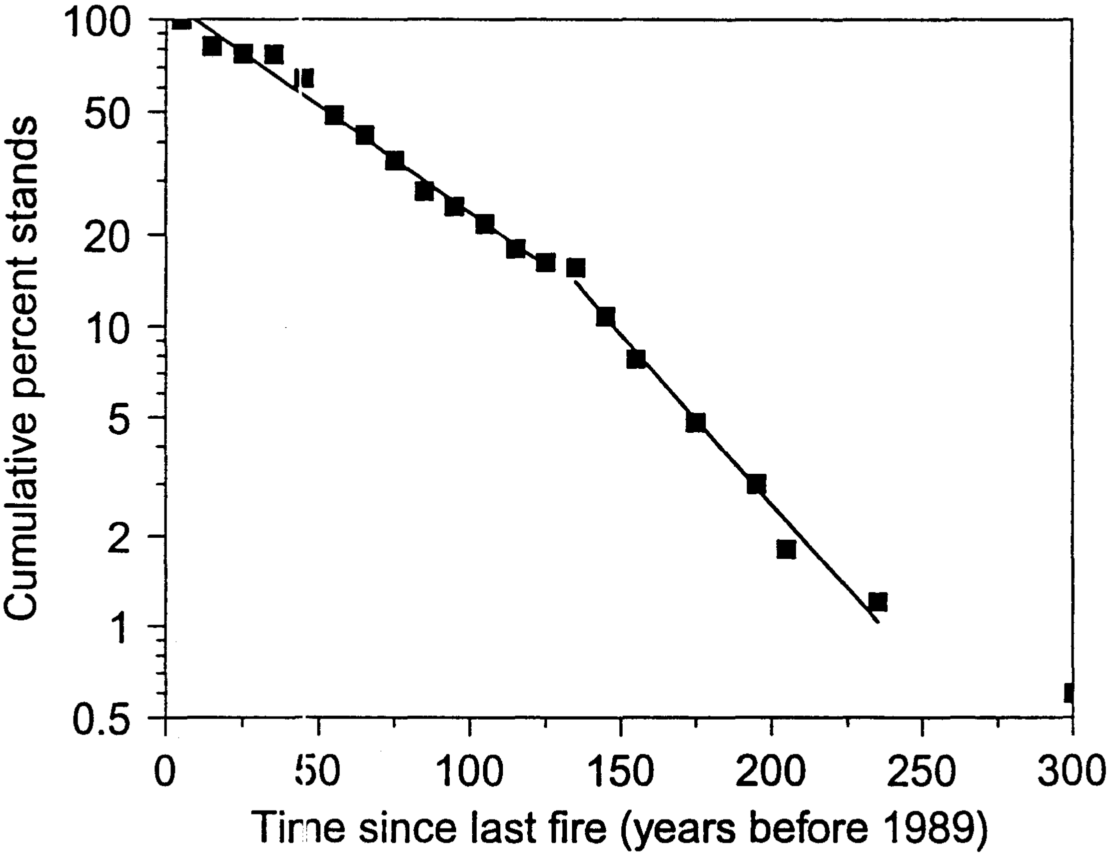

Figure 4.3. The mixed survival distribution from Wood Buffalo National Park plotted in 10 year age classes using a semi-logarithmic scale. Logarithmic regression lines have been fit to the periods of apparently constant fire frequency before and after 1860.

Table 4.1. Fire cycle estimates for different vegetation types, and the vegetation types which exhibit significantly different fire cycles.

Vegetation type	N	Fire cycle (years) Mean	Fire cycle (years) 95% confidence limits	Vegetation types with a significantly different fire cycle
Jack pine	35	39	29 - 56	Black spruce***, White spruce***
Aspen	18	39	26 - 68	Black spruce**, White spruce**
Black spruce	64	78	65 - 109	Jack pine***, Aspen**
White spruce	31	96	71 - 142	Jack pine***, Aspen**

$^{**}p \leq .01$, $^{***}p \leq .001$

Table 4.2. Fire cycle estimates for different mean waterbreak distance classes, and the waterbreak classes with significantly different fire cycles.

Mean distance to waterbreaks (km)	N	Fire cycle (years) Mean	95% confidence limits	Waterbreak classes with a significantly different fire cycle
Close (0.00 - 2.99)	61	81	64 - 107	Far*
Medium (3.00 - 5.99)	63	60	49 - 82	
Far (6.00 - 17.99)	42	49	39 - 71	Close*

*$p \leq .05$

differences in the MWD (Table 4.3), with jack pine and aspen stands exhibiting a higher MWD than white spruce. When the survival model included both vegetation classes and the MWD as covariates, vegetation type was siginficant ($p \leq .01$) and MWD was non-significant.

Fire scarred jack pines were found in 12 of the 35 pine dominated sites. One fire scarred individual was collected from each of these sites. Eight sites had trees with one fire scar, two sites had trees with scars from two different fires, one site had trees with scars from three different fires, and one site had trees with scars from four different fires. The 12 intervals between the estimated establishment of a tree and the first fire scar averaged 42 years, and the 7 intervals between consecutive fire scars on a tree averaged 40 years.

The black spruce survival distribution exhibits a break in its slope at 1860 (Fig. 4.4). The survival distributions of the near and medium MWD classes also exhibit breaks in their slopes at 1860 (Fig. 4.5). Regression lines were fit to the pre- and post- 1860 time periods for the whole park (Fig. 4.3), the black spruce dominated sites (Fig. 4.4) and the near and medium MWD classes (Fig. 4.5). The 300 year TSLF date was not included in the regression models since its inclusion resulted in poor regression models. In all four distributions the fire cycle estimate obtained from the slope of the regression line was significantly slower in the post- 1860 time period than that in the pre- 1860 period (Table 4.4).

Table 4.3. The mean waterbreak distance for each vegetation type, and the vegetation types with which the mean waterbreak distance is significantly different.

Vegetation type	N	Mean waterbreak distance (km)	Vegetation types with significantly different mean waterbreak distances
Jack pine	35	7.24	Black spruce**, White spruce***
Aspen	18	5.45	White spruce**
Black spruce	64	4.28	Jack pine**, White spruce*
White spruce	31	2.71	Jack pine***, Aspen**, Black spruce*

$^{*}p \leq .05$, $^{**}p \leq .01$, $^{***}p \leq .001$

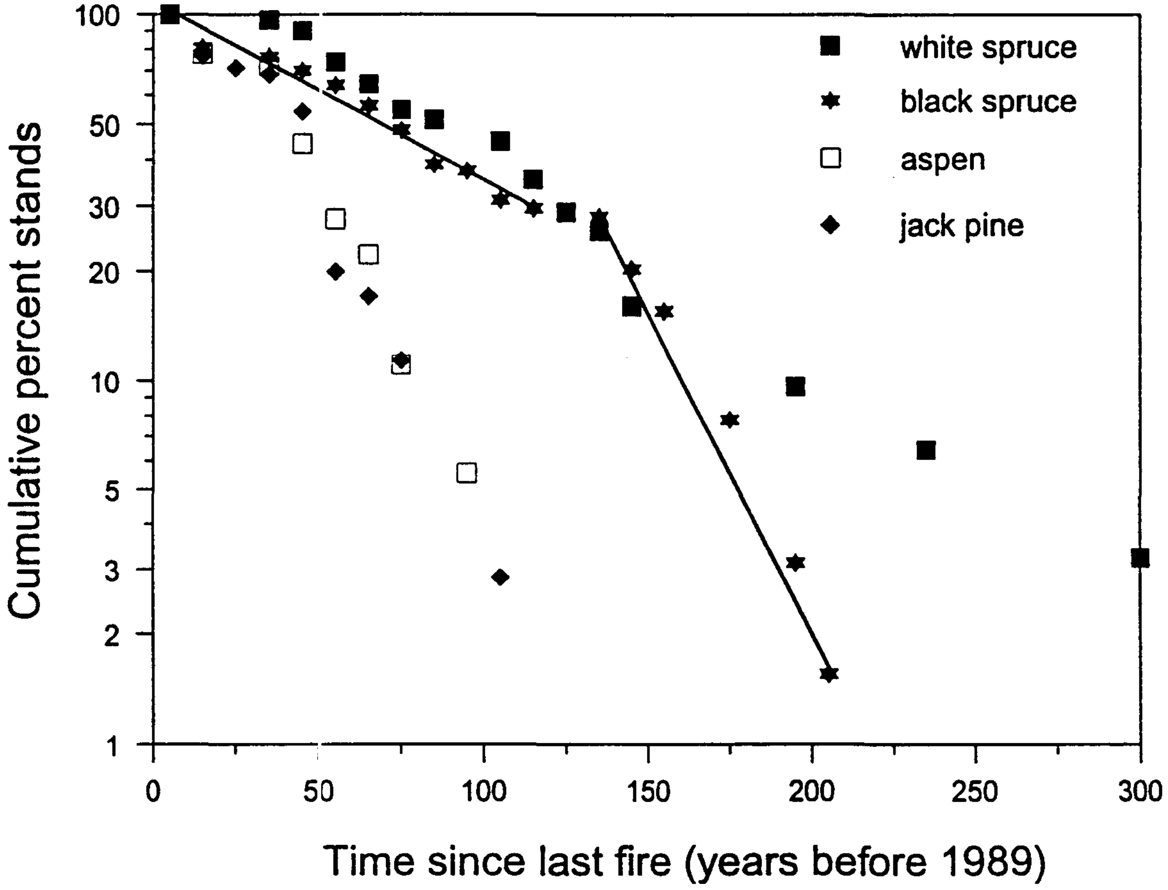

Figure 4.4. The survival distributions for the sites dominated by the four most frequent vegetation types in Wood Buffalo National Park, plotted in 10 year age classes on a semi-logarithmic scale. A logarithmic regression line has been fit to the black spruce distribution for the periods of apparently constant fire frequency before and after 1860.

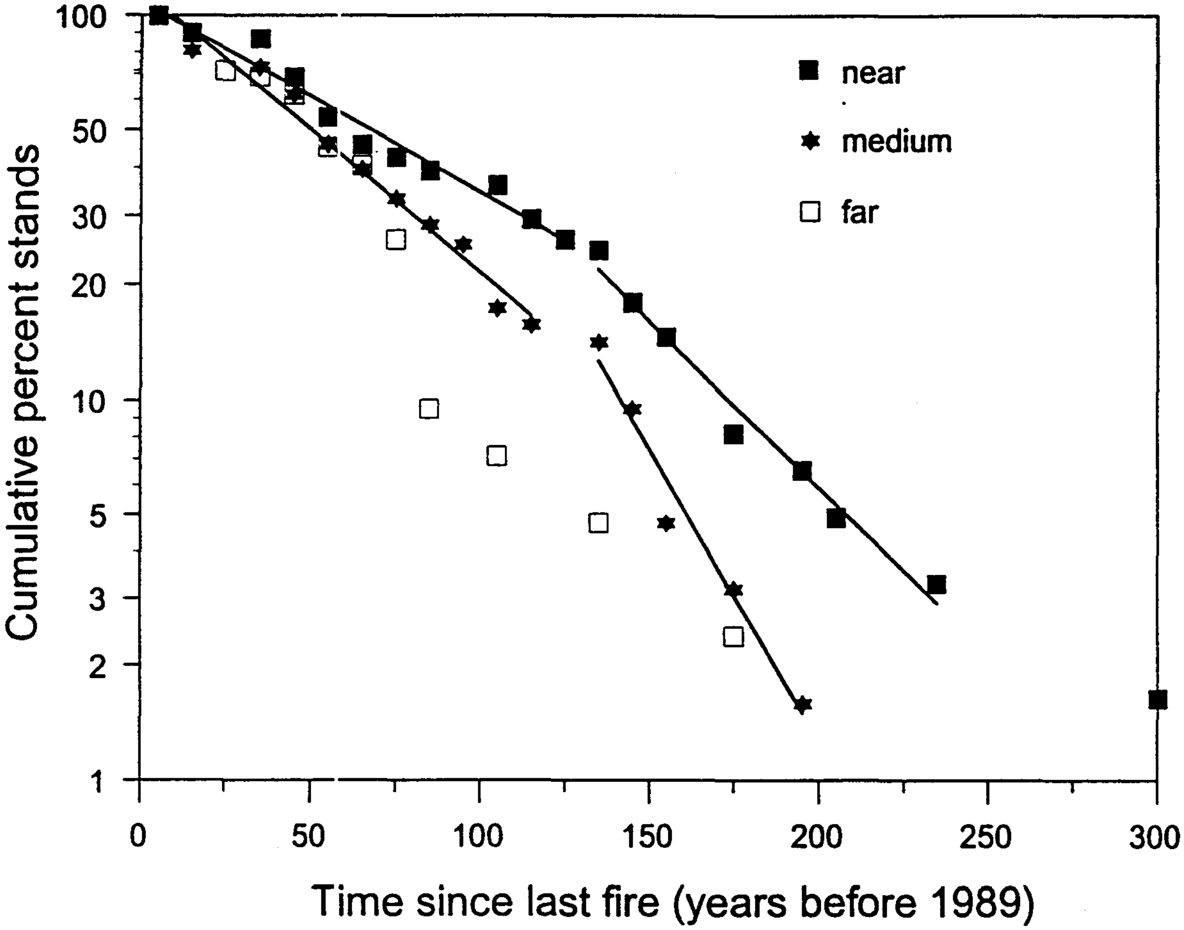

Figure 4.5. The survival distribution for sites in Wood Buffalo National Park classed by the mean distance to waterbreaks: near (0.00 - 2.99 km), medium (3.00 - 5.99 km) and far (6.00 - 17.99 km). Data are in 10 year age classes and plotted on a semi-logarithmic scale. Logarithmic regression lines have been fit to the near and medium distance class distributions for the periods of apparently constant fire frequency before and after 1860.

Table 4.4. Fire cycles estimates from the pre- and post- 1860 time periods for the mixed time since last fire distributions. The R^2 and number of age classes are given for the logarithmic regressions used to estimate the fire cycle. Fire cycles in the two time periods identified in each distribution are signficantly different at a $p < .001$.

Time period	Fire cycle (years) Mean	Fire cycle (years) 95% confidence limits	R^2	N
All WBNP				
1860 - 1989	63	55 - 68	.99	13
1750 - 1859	38	34 - 43	.98	7
Near waterbreak class (0.00 - 2.99 km)				
1860 - 1989	87	78 - 100	.97	11
1750 - 1859	49	44 - 57	.98	7
Medium waterbreak class (3.00 - 5.99 km)				
1870 - 1989	59	54 - 65	.98	11
1790 - 1859	28	23 - 35	.97	5
Black spruce dominated sites				
1870 - 1989	89	80 - 100	.97	11
1780 - 1859	25	22 - 28	.98	6

4.5 DISCUSSION

The results of this study support the contention made in other studies that, in the boreal forest of North America, fire frequency is significantly higher in jack pine and aspen forests than in black and white spruce forests (Table 4.1). The similarity of the 39 year fire cycle estimate from the mean age of jack pine dominated stands and the 40-42 year mean fire interval estimates from the fire scars on jack pines suggests that the estimates are reliable. The fire cycle estimates for the different vegetation types in (WBNP) (Table 4.1) compare well with those from parts of the North American boreal forest (Table 4.5), with the exception of southern Quebec.

The differences in fire cycle exhibited by the different vegetation types is related to mean waterbreak distance (MWD) (Tables 4.2 and 4.3), indicating that MWD does affect the ability of fires to burn an area. That MWD cannot fully explain the fire cycles in the different vegetation types suggests that other factors related to vegetation are important. For example, jack pine and aspen are typically found on drier sites than are black or white spruce (Dix and Swan 1971, Carleton and Maycock 1978, Airphoto Analysis Associates 1979), and difference in site moisture could affect live fuel flammability and therefore fire frequency (cf. Quirk and Sykes 1971, Heinselman 1973, Zackrisson 1977, Romme and Knight 1981).

It is notable that observations of wild and experimental fires suggest that, given similar short term weather conditions, the rate of fire spread should be the same in spruce-lichen woodland, boreal spruce, mature and immature jackpine forests, and slower in aspen forests (Forestry Canada 1992). These differences in fire behaviour

Table 4.5. Fire cycle estimates from different vegetation types in the North American boreal forest.

Dominant vegetation	Fire cyle (years)	Location	Study
Pine and aspen			
Jack pine	28 - 54	northern Alberta and Saskatchewan	Carroll and Bliss 1982
Aspen[1]	60	central Alaska	Yarie 1981
Jack pine & aspen	70	central Quebec	Cogbill 1985
Mixed pine	97 - 162	southern Quebec	Bergeron 1991
Spruce			
Black spruce[1]	100	central Alaska	Yarie 1981
White spruce[1]	113	central Alaska	Yarie 1981
Mixed spruce	130	central Quebec	Cogbill 1985
Mixed spruce	159-168	southern Quebec	Bergeron 1991

[1] Yarie (1981) provided estimates over different time periods and using different models; these estimates were determined using all TSLF data and a Weibull model.

do not agree with the differences in fire frequency shown to exist between vegetation types (Table 4.1). Since the focus of these studies was the relation between fuel dryness and rate of spread, however, it is likely that they only observed short fire runs in areas where waterbreaks would not affect the rate of fire spread (eg. Stocks 1987, 1989). If the mean rate of fire spread was measured at the landscape scale, then the differences in MWD in the different vegetation types (Table 4.3) would likely modify the rate of spread such that it would be faster, for example, in jackpine than in white spruce forests. In addition, they note that longer term drying should affect the rate of fire spread, but their data were not adequate to assess the relationship (Forestry Canada 1992). Long term drying would likely affect vegetation flammability on dry sites, such as dominated by jack pine, more than it would vegetation such as black and white spruce which dominate moist sites.

A temporal change in fire frequency at 1860 was apparent in the survival distribution for WBNP (Fig. 4.3), black spruce (Fig. 4.4) and the near and medium MWD classes (Fig. 4.5). In all four distributions the pre-1860 fire cycle was significantly faster (25 - 49 years) than the post-1860 fire cycle (59 - 89 years) (Table 4.4). It is probable that a break is not apparent in the white spruce survival distribution because, since only three stands comprise the pre-1839 portion of its distribution which diverges from the black spruce distribution, the shape of this portion is easily biased. Similarly, the lack of a break in the far MWD class is probably due to there being only four stands in the pre-1910 period. The jack pine and aspen survival distributions do not extend far enough back in time to exhibit the break.

A reduction in boreal forest fire frequency following 1870 was found in Quebec (Bergeron 1991) and in northern Sweden (Engelmark et al. 1994). The similar timing of the reduced fire frequency in Sweden, Quebec and northern Alberta suggests a climatic cause. Indeed, Bergeron and Archembault (1993) found that a tree ring-width chronology that was positively related to June precipitation and negatively related to the fire weather Drought Code (Archembault and Bergeron 1992) exhibited greater ring-widths between 1860 and 1980 than between 1600 and 1860, therefore suggesting an increase in precipitation as the cause of their post- 1879 reduced fire frequency.

Since precipitation exerts more of an influence on annual area burned in WBNP than does temperature (Chapter 3), it is likely that the post -1860 decline in fire frequency in WBNP was also due to an increase in precipitation. Tree ring-width records from WBNP have also been found to be positively correlated with June precipitation, negatively correlated with fire weather and annual area burned (Chapter 2), and negatively correlated with the mean annual percent area burned in WBNP in 5 year periods between 1850 and 1989 (Chapter 3). The tree ring-width records only extend to 1833, though and are therefore not useful for comparing the pre- and post-1860 periods. There is some evidence from a spatial network of tree ring sites that the period 1602-1900, relative to the period 1901-1970, had a high pressure anomaly situated over the southern Yukon (Fritts 1991). A higher frequency of high pressure systems in the area would result in more frequent years with warm and dry conditions that are conducive to high fire activity to the WBNP area (cf. Chapter 3). Further research on the palaeoclimate in this region is required, however, before a climatic cause for the change in fire frequency can be specified.

It is also possible that changes in aboriginal burning practices could have caused the temporal change in fire frequency in WBNP. Ethnohistorical research in northern Alberta has found that during the historical period, aboriginals have primarily burned small areas in wetland meadows and along stream courses to improve browse for horses and large game (Lewis 1977, Lewis and Ferguson 1988). Upland forests were sometimes burned to clear deadfall, but were usually protected as prime habitat for some trap animals. Aboriginals in the area were introduced to the trapping economy by 1780 and had become reliant on it by 1860 (Yerbury 1986). It is therefore possible that prior to dependency on trapping, more wetland areas would have been burned to increase browse for hunted large game, and these fires would have extended into the surrounding forest and increased the fire frequency. While this scenario is plausible, the changes in the aboriginal economy occurred incrementally, and it is hard to envision that the changes in burning practices that may have accompanied the reduction in large game hunting would have more than halved the fire frequency. However, until a climatic cause for the change in fire frequency can be proven, this aboriginal cause should not be ruled out.

CHAPTER 5

FIRE HISTORY OF JACK PINE AND BLACK SPRUCE FORESTS IN NORTHERN ALBERTA FROM FOSSIL POLLEN AND CHARCOAL RECORDS

5.1 INTRODUCTION

The composition and dynamics of plant communities are greatly affected by disturbance factors such as fire, wind and insects (Pickett and White 1985). Fossils of pollen and charcoal contained in lake sediments that are finely resolved in time (<20 years/sample) may be one means by which the long term frequency of fires can be estimated and the response of the community to the fires to be inferred (eg. Swain 1973, 1978, 1980, Green 1982, Patterson and Backman 1988, Clark et al. 1989, Clark 1990).

Most palaeo-fire studies have employed annually laminated (varved) lake sediments (eg. Swain 1973, 1978, Cwynar 1978, Clark et al. 1989, Clark 1990, MacDonald et al. 1991) because they offer good chronological control and the pollen and charcoal fossils they contain have not been temporally mixed. Varved sediments are not common, however, because the lakes with the small surface areas and great depths required for the preservation of varves (Larsen and MacDonald 1993) are not frequent. Some studies using non-laminated (massive) sediments have been able to relate radio-isotope dated pollen and charcoal indicators of fire with historically known local fires (eg. Swain 1980, Patterson and Backman 1988), and have identified vegetation succession patterns in fossil pollen records using time series analysis (eg. Green 1981). However, no study using massive lake sediments has yet estimated the mean fire frequency of the surrounding forest and validated this estimate through comparison with a known fire frequency for the region. If such a validation could be made, then fossils of charcoal and pollen contained in the common massive lake sediments could be used to reconstruct the fire frequency of many different forests and environments.

In this study I create fine resolution fossil pollen and macroscopic charcoal records from two lakes in the boreal forest of northern Alberta. Fariya Lake is surrounded by upland jack pine forest and Ninisith Lake is surrounded by lowland black spruce forest. I test three hypotheses regarding fossil pollen and macroscopic charcoal records of fire-vegetation dynamics. First, I use time series analysis to test whether the fossil pollen records from these lakes exhibit a repeated pattern of post-fire vegetation succession. Second, I test the hypothesis that the radiocarbon dated fossil pollen and macroscopic charcoal data do record fires known through local dendrochronological fire history research. Third, I test the hypothesis that the fire frequency estimates obtained from the two lakes are similar to estimates from regional scale dendrochronological fire history records from sites with similar vegetation and mean distances to mapped waterbodies around the site which could affect fire spread into the site.

5.2 STUDY AREA

5.2.1 Regional conditions

The study was conducted on lake sediments recovered from Fariya Lake and Ninisith Lake (informal names), located in the central boreal forest of northern Alberta (Fig. 5.1). The regional vegetation is dominated by *Pinus banksiana* (jack pine), *Picea mariana* (black spruce), *Picea glauca* (white spruce), *Populus tremuloides* (aspen),and *Betula papyrifera* (paper birch) (Rowe 1972, Franklin 1993). The area has a dry continental climate, with a mean annual temperature of -3.3°C and a mean total annual precipitation of 36.5 cm at Ft. Smith (Fig. 5.1, 1950-1980 climate normals, Environment Canada 1982). During the 4 summer months (May 1 - August 31), the mean monthly temperature is 12.9°C and the mean total precipitation is 16.9 cm (Environment Canada 1982).

Fire records have been kept for 44, 807 km^2 Wood Buffalo National Park (WBNP), in which Ninisith Lake is located (Fig. 5.1), for the period 1950-89 (unpublished WBNP Warden Service data). These records indicate that up to 100 fires can occur in a year, that the largest fires can be up to 1800 km^2, and that up to 6500 km^2 (14.5% of WBNP) can burn in a year. A dendrochronological fire history of WBNP (Chapter 4) found a mean fire cycle of 63 years. Note that the fire cycle is the number of years required to burn an area equivalent to the study area (Johnson and Van Wagner 1985). Since the WBNP fire history data conform to a negative exponential distribution the fire cycle is also equal to the mean fire interval (MFI), which is the mean number of years between successive fire events at a site. Given

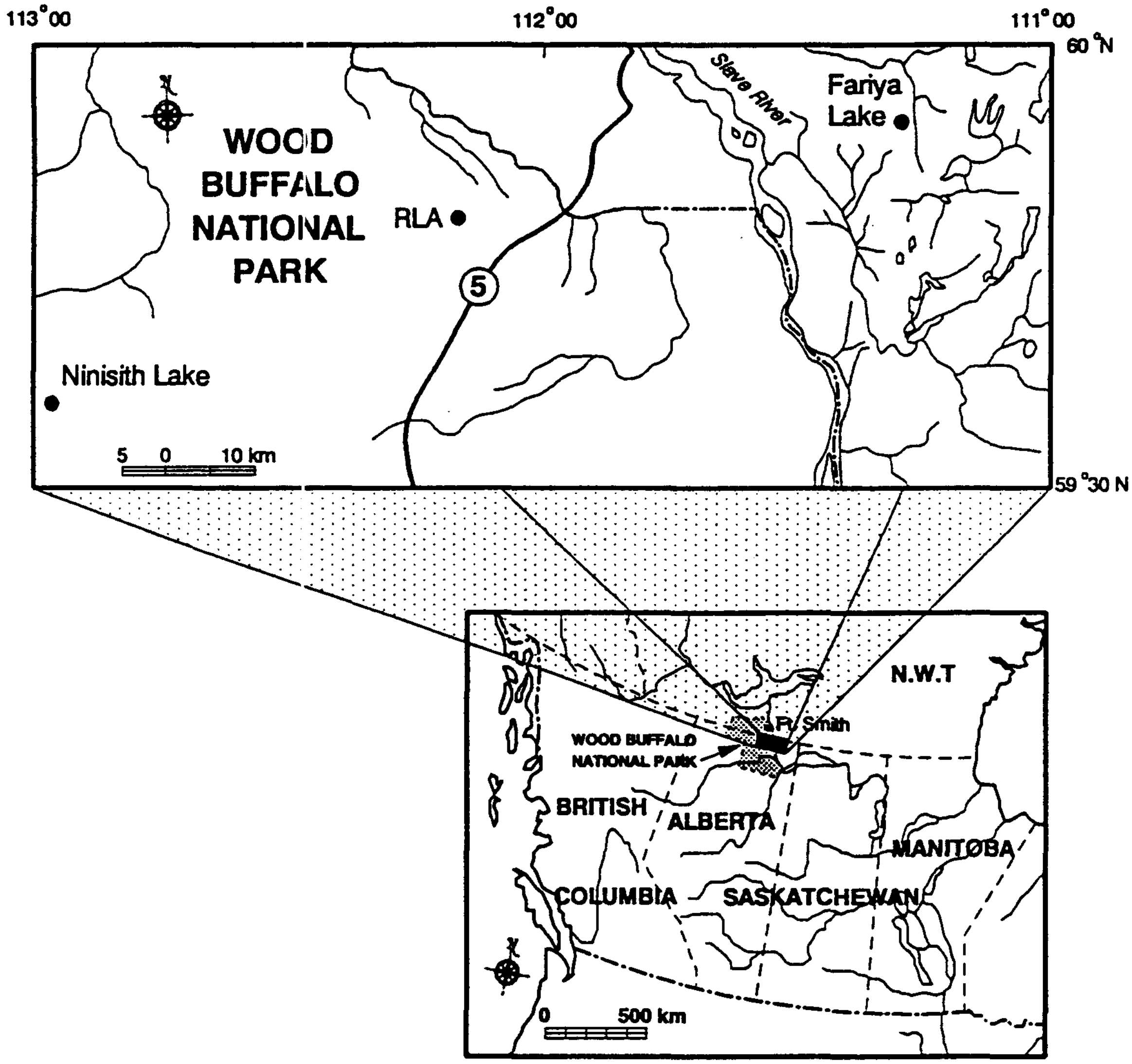

Figure 5.1. Location of Fariya Lake, Ninisith Lake and the previously published RLA.

this equality, the frequency is the inverse of the fire cycle or MFI (Johnson and Van Wagner 1985). In this work I will use the term fire frequency unless referring to a specific estimate, in which case it will be noted whether the estimate is of the fire cycle or MFI. The fire cycle in WBNP (Chapter 4) was also found to vary by vegetation type, ranging from 39 years in jack pine and aspen dominated forests, to 78 years in black spruce dominated forests, to 96 years in white spruce dominated forests. The fire cycle was also related to the mean waterbreak distance (MWD), ranging from 81 years in sites with a 0.00-2.99 km MWD, to 60 years in sites with a 3.00-5.99 MWD, and to 42 years in sites with a 6.00-17.99 km MWD. The MWD was calculated as the mean distance from the lake to the first waterbreak around the lake in each of the eight cardinal directions, as shown on 1 : 250 000 topographic maps. The measurement was done in this way so that the MWD was comparable to those obtained in a dendrochronological fire history study done in WBNP (Chapter 4).

5.2.2 Fariya Lake

Fariya Lake (Fig. 5.2) has a 1.2 ha surface area, a 5.6 m maximum depth, no inflowing or outflowing streams, a ~6.0 ha watershed, and a 1.1 km MWD. The lake is formed in a basin in granitic rocks of the Precambrian Canadian Shield. Rock outcrops rise ~10 m immediately around the lake. The forest is dominated by open jack pine stands on exposed rock benches and slopes (Fig. 5.2). Paper birch (*Betula papyrifera*) is frequent in the small areas between ridges where there is some soil accumulation. Crustose lichens dominated the floor of the open jack pine forests

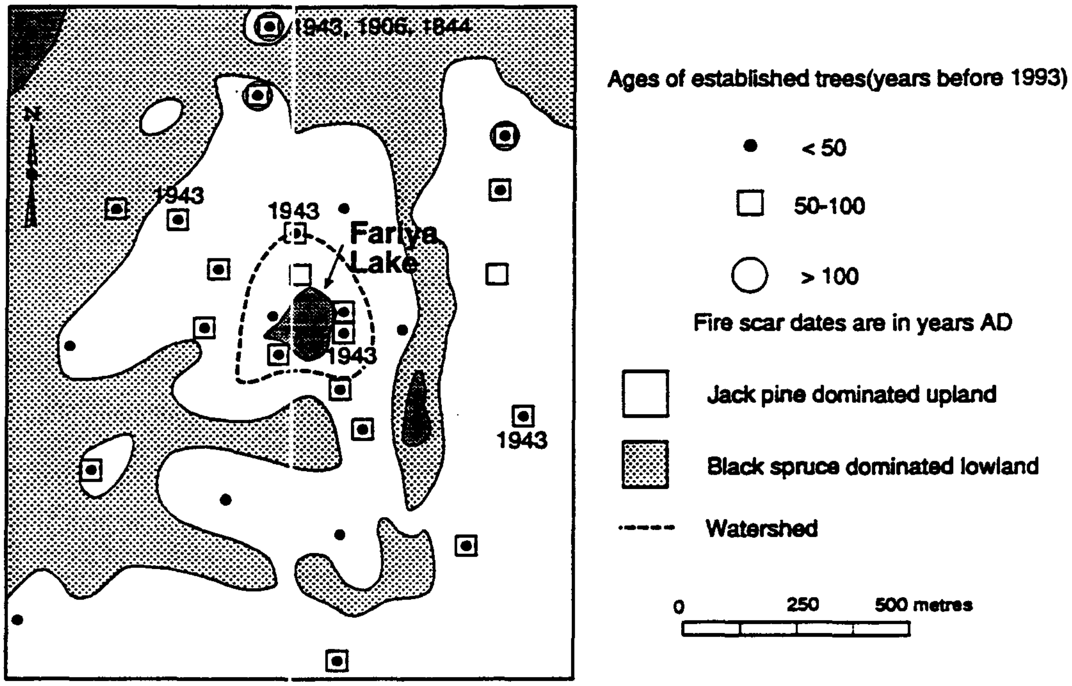

Figure 5.2. Fire history, vegetation types and watershed position around Fariya Lake.

although blueberry (*Vaccinium myrtilloides*) is found in some hollows. Black spruce forests dominate in the wet lowland areas in local topographic depressions (Fig. 5.2).

The area around Fariya Lake was surveyed for fire scars (cf. Arno and Sneck 1977) in July of 1993. Disks which contained fire scars were cut from a total of 8 trees at 5 sites. In addition, increment bores from the base of 124 trees at 27 sites were taken to determine if there were pulses of tree recruitment following the fire events indicated by the fire scars. The disks and increment bore samples were sanded and their ages were determined using a stereomicroscope. The year of fire scar formation, and the age classes of trees found at each site are provided in Fig. 5.2. The 1943 fire was extensive, since trees younger than 50 years that would have recruited following that fire were found in 25 of the 27 stands. The destruction due to the 1943 fire was not complete, though, since 20 of the 27 stands have trees 50-100 years old that would most likely have recruited following the 1906 fire. Only 3 stands had trees greater than 100 years old.

5.2.3 Ninisith Lake

Ninisith Lake (Fig. 5.3) has a 1.0 ha surface area, a 3.2 m maximum depth, no inflowing or outflowing streams, a ~22.0 ha watershed, and a 4.1 km MWD. The lake is formed in a hollow between several eskers. The topography is flat for several kilometres to the east of the lake, and is flat for ~30 m in the other directions beyond which the eskers steeply rise ~ 20 metres. The vegetation around the lake is dominated by black spruce in the lowlying poorly drained areas, and by jack pine and some

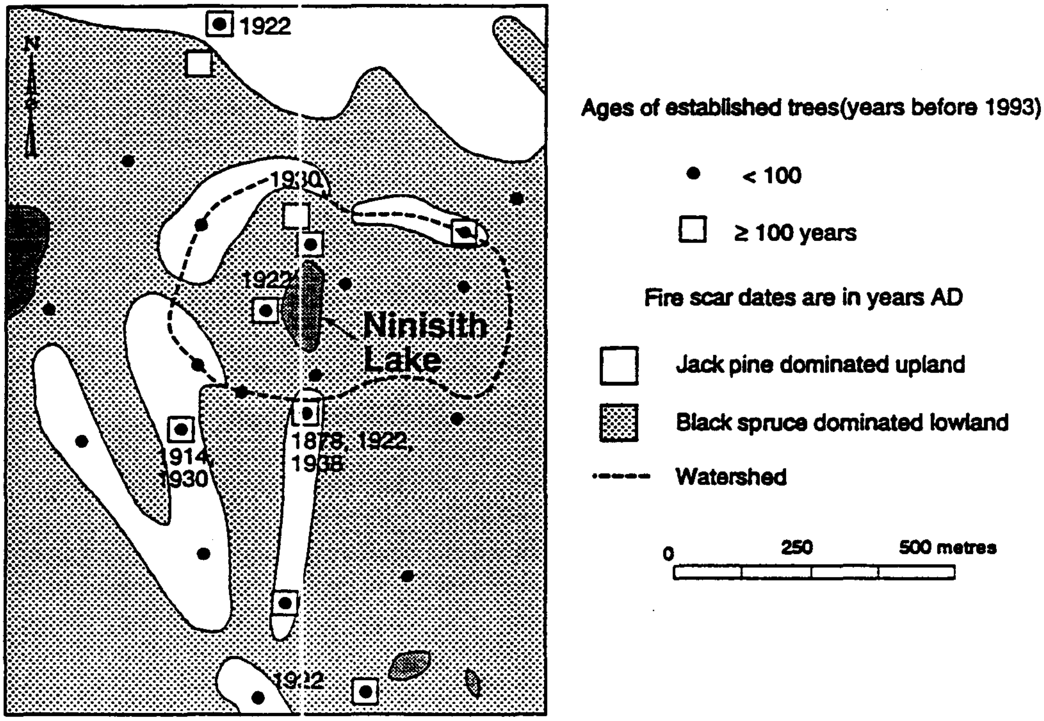

Figure 5.3. Fire history, vegetation types and watershed position around Ninisith Lake.

aspen on the well drained eskers. The black spruce sites also contained larch (*Larix laracina*), paper birch, shrub alder (*Alnus crispa*), shrub willow (*Salix* spp.), labradortea (*Ledum groenlandicum*), and a groundlayer of mosses and lichens. The jack pine sites had an open understorey frequently consisting of prickly rose (*Rosa acicularis*), bearberry (*Arctostaphylos uva-ursi*) and fruticose lichens.

The area around Ninisith Lake was surveyed for fire scars in June of 1993. Disks which contained fire scars were cut from a total of 6 trees at 6 sites. In addition, increment bore samples from 127 trees from 25 sites were taken to determine if there were pulses of tree recruitment following the fire events indicated by the fire scars. The year of fire scar formation, and the age classes of trees found at each site is indicated in Fig. 5.3. A series of four fires occurred early in the 20th century, with the fires in 1922 (scars in 4 sites) and 1930 (scars in 2 sites) appearing to be the most extensive. Trees younger than 100 years that likely would have established following these fires were found in 23 of the 25 stands. Trees older than 100 years were found in 10 of the 25 stands.

5.3 METHODS

5.3.1 Core Recovery and Sub-sampling

Lake sediments were retrieved from Fariya Lake and Ninisith Lake using a modified Livingstone piston corer (Wright et al. 1984) in late March of 1991. The top 76 cm of the Fariya Lake sediments and the top 84 cm of the Ninisith Lake sediments were recovered using clear acrylic tubes that allowed the sediment-water interface to be seen. To facilitate travel, the sediments were slghtly dewatered in the field by drilling holes at various depths in the core. Following dewatering the Fariya Lake core had shrunk to 58 cm and the Ninisith Lake core had shrunk to 70 cm. The sediments within the acrylic tube cores were extruded vertically in the laboratory by removing the bottom plug, inserting a piston and then using a scissor jack to drive the piston and sediments upwards. The sediments were sliced off in 2 cm thick sections which were subsequently sliced into 2.5 mm thick sections.

The sediments from both lakes were organic rich gyttjas. Contiguous 2 cm^3 samples from the top 32 cm of the Fariya Lake sediments and the top 24 cm of the Ninisith Lake sediments were analyzed for organic content through loss on ignition for 1 hour at 500 °C (Dean 1974). The mean organic content of the Fariya Lake samples was 73.3% (range: 71.8 to 76.1%) and of the Ninisith Lake samples was 87.0% (range: 84.0 to 89.2%).

5.3.2 Chronology Construction

Radiocarbon dates obtained for both Fariya Lake and Ninisith Lake (Table 5.1) provide a sediment chronology. This chronology allows the calculation of pollen and charcoal accumulation rates and the comparison of the times of inferred palaeo-fires with the local dendrochronological fire records. The calendar year for each radiocarbon date was determined by correcting for changes in atmospheric ^{14}C content (Stuiver and Reimer 1993). The absolute depth at which samples for radiocarbon dating were taken from the extruded acrylic tube sediments had been affected by the

Table 5.1. Radiocarbon ages and sedimentation rates from Fariya Lake and Ninisith Lake.

Depth (cm)		Lab Number	^{14}C Age (Years BP)	Calendar Age	Sedimentation Rate (mm/yr)	
Non-dewatered	Dewatered				Dewatered	Non-dewatered
			FARIYA LAKE			
40.6-41.9	31-32	Beta-54928[1]	510+/- 70	1418 AD	.55	.72
90-95	-	Beta-48091[2]	1250+/- 80	772 AD	-	.76
			NINISITH LAKE			
63.8-64.2	53.2-53.5	Beta-54927[3]	1360 +/- 70	657 AD	.40	.48
90-95	-	Beta-47511[2]	1950 +/- 80	58 AD	-	.48

[1] AMS date on algal gyttja, [2] bulk sediment date on algal gyttja, [3] AMS date on a wood macro-fossil

dewatering and resultant compaction of these sediments, while it had not been affected for the radiocarbon samples taken from lower core sections. A linear correction factor, calculated by dividing the length of the sediment in the acrylic tube prior to dewatering by the dewatered length of the core, was therefore used to estimate the original depth of the radiocarbon samples. The sedimentation rates estimated from the radiocarbon ages at different depths coud then be compared for consistency.

In Fariya Lake, the sedimentation rates obtained using the calendar ages of the samples at the non-dewatered depths of 40.6-41.9 cm and 90-95 cm (Table 5.1) are very similar (0.72 and 0.76 mm/yr). In Ninisith Lake, the sedimentation rates obtained using the calendar ages of the samples at the non-dewatered depths of 63.8-64.2 cm and 90-95 cm (Table 1) are identical (0.48 mm/yr). These results suggest that the radiocarbon dates provide a reliable indication of the average sedimentation rate. In Fariya Lake the dewatered sedimentation rate of 0.55 mm/yr suggests that the average number of years in each 2.5 mm thick sample is 4.55 years. In Ninisith Lake the dewatered sedimentation rate of 0.40 mm/yr suggests that the average number of years in each 2.5 mm thick sample is 6.25 years.

Pb-210 analyses were undertaken by Flett Research Ltd. (Winnipeg, Manitoba) on samples from the upper 12 cm of the Fariya Lake and the upper 8 cm of the Ninisith Lake sediments The ages obtained were 2-3X younger than those suggested by the radiocarbon chronologies. Following a discussion with Dr. R. Flett, it was recognized that draining of the sediments, undertaken to allow sufficient sediment consolidation for extrusion and sampling, resulted in Pb-210 being brought down core and leading to erroneously young ages.

5.3.3 Pollen Analysis

A sample with a 1 cm^2 surface area was taken from each 2.5 mm thick sample from the top 32 cm of the Fariya Lake sediments (128 samples) and the top 24 cm of the Ninisith Lake sediments (96 samples). Each sample was processed for fossil pollen and microscopic charcoal analysis using standard methods (Faegri et al. 1989). A known quantity of pre-acetolyzed *Lycopodium* spores were added to the samples prior to processing to allow the calculation of Pollen Accumulation Rates (PARs) (Stockmarr 1971) and Charcoal Accumulation Rates (CHARs). Pollen percentages were calculated using the sum of total terrestrial pollen grains, with Cyperaceae calculated outside of the sum. Between 388.5 and 527 (mean = 429) terrestrial pollen grains were counted from Fariya Lake sample and between 382.5 and 461 (mean = 423) terrestrial pollen grains were counted from each Ninisith Lake sample. Identifiable pollen from non-terrestrial plants and spores were also counted. Palynomorphs were identified using a reference collection and illustrated keys (Kapp 1969, McAndrews et al. 1973). *Picea* cf. *glauca* and *Picea* cf. *mariana* pollen were differentiated using the qualitative criteria outlined by Hansen and Engstrom (1985).

5.3.4 Charcoal Analysis

Microscopic charcoal was counted using a 124 x 124 μm ocular grid divided into 10 x 10 cells. All charcoal pieces that fell into this grid while traversing the slide during pollen counting were recorded. Microscopic charcoal pieces were tallied in the following size classes: 75-374 μm^2 , 375-679 μm^2, 680-1434 μm^2, 1435-2199 μm^2 and >2200 μm^2. Between 12 and 202 microscopic charcoal pieces were identified in each Fariya Lake sample, and between 9 and 307 microscopic charcoal pieces were identified in each Ninisith Lake sample.

A second sample with a 1 cm^2 surface area was taken from each of the same samples and processed for macroscopic charcoal. The samples were soaked in a solution of 5% $Na_4P_2O_7$ for 7 days and then washed through a No. 200 brass sieve (75 μm openings) using a fine brush to disaggregate them. The fragments retained in the sieve were washed into a petri dish and were then counted and measured using a Nikon stereomicroscope with a magnification of 63X. The length and width of every charcoal fragment in each sample was measured and multiplied to estimate its area. Between 5 and 107 macroscopic charcoal fragments were identified in the Fariya Lake samples, and between 0 and 41 macroscopic charcoal fragments were identified in the Ninisith Lake samples. The smallest fragments counted were 2000 μm^2.

5.3.5 Succession

The pollen records from each lake were examined for post-fire vegetation succession patterns, which could provide indications of fire occurrence, using cross correlation analysis (Gottman 1981, Green 1982, Clark et al. 1989). Cross correlation analysis involves correlating the time series of a taxon with that of another taxon at different time lags. Statistically significant correlations indicate the number of years which peaks in pollen production from one taxon follow that of another taxon. Cross correlations were calculated using SYSTAT (Wilkinson 1988). In my use of this method I assume that pollen production of the dominant local tree taxon at a site reaches its peak just before a fire destroys most of the local trees. At Fariya Lake the samples were cross-correlated against pollen from the locally dominant jack pine, and at Ninisith Lake the samples were cross-correlated against pollen from the locally dominant black spruce. To reduce the chance of spurious correlations, I used only those terrestrial taxa present in more than 10% of the samples.

I required that the taxa exhibit significant cross-correlations using both the Pollen Accumulation Rate (PAR) and pollen percentage data and that these significant correlations occur at the same lag time. This was required since changes in PARs and percentages can be caused by various factors other than changes in the actual abundance of the plant taxa. Successional patterns were not assessed using cross correlations against the macroscopic charcoal record for three reasons. First, the amount of charcoal produced by a fire is not related just to fire size and fire proximity, but is also related to the amount of fuel, the fire type (heading or backing) and the fire intensity (Nelson and Ward 1980, Chandler et al. 1983). Second, the macroscopic charcoal data are not normally distributed. Third, it is useful to maintain the macroscopic charcoal and fossil pollen records as independent indicators of local palaeo-fires.

5.3.6 Palaeo-Fire History

Past local fire events were identified in the lake sediments when peaks in macroscopic charcoal were coincident with declines in the PARs or pollen percentages of the locally dominant tree taxa and the initiation of vegetation succession. It has been shown theoretically and empirically that relatively heavy macroscopic charcoal represent local fires quite well, while lighter microscopic charcoal can represent either local or regional fires (Patterson et al. 1987, Clark 1988, 1990, MacDonald et al. 1991). Peaks in macroscopic charcoal are therefore used as the primary line of evidence for local palaeo-fire occurrences. However, the microscopic charcoal records are still presented to assess how well they compare with the macroscopic characoal record and the known and inferred palaeo-fire record.

Declines in pollen from late successional tree taxa and subsequent successional patterns in pollen from herbaceous and woody taxa have also been shown to indicate local palaeo-fires quite well (Swain 1973, 1978, 1980, Patterson and Backman 1988, Clark et al. 1989, MacDonald et al. 1991). I allow variations in either the PARs or percentages of the successional pollen records to be a secondary indicator of palaeo-fires since both pollen measures are subject to error. PARs may falsely indicate variations in the local abundance of a taxa because of changes in sedimentation rates that cannot be recognized in the massive sediments. Percentages may falsely indicate variations in the abundance of a taxon because the multi-collinear nature of the pollen percentage means that variations in the pollen production of one taxon will cause variations in the pollen percentages of other taxon. In addition, based on aerodynamic principles, the pollen records of the locally dominant tree taxon will not just represent the local populations. Approximately 30% of the relatively light jack pine and black spruce pollen deposited in the center of Fariya and Ninisith Lakes should come from within 1 km of the lake basins (Prentice 1985, Sugita 1993).

The pollen records presented to assess palaeo-fire occurrences are given as the raw data and as the data smoothed using a 5 term binomial filter (weights: 0.0625, 0.25, 0.375, 0.25, 0.0625) (Howarth and Rogers 1992). Smoothing was employed to remove short term variations that could obscure the successional signal. Short term variations may result from factors such as regional fires, variations in sample sizes, and the fact that pollen counts are only a statistical sample.

5.4 RESULTS

Short term (< 100 year) variations, possibly the result of post-fire succession, are apparent in the PAR and percentage records of terrestrial taxa at Fariya Lake (Figs. 5.4 and 5.5) and Ninisith Lake (Figs. 5.6 and 5.7). No marked long term (> 100 year) variations are apparent in the PAR or pollen percentage records from either lake.

The Gramineae PAR and percentage records from Fariya Lake exhibited significant cross-correlation peaks at 0-23 years and 55-59 years after peaks in *Pinus* PARs and percentages (Fig. 5.8). No other taxa from Fariya Lake or Ninisith Lake exhibited contemporaneous significant cross-correlations using the PAR and pollen percentage data.

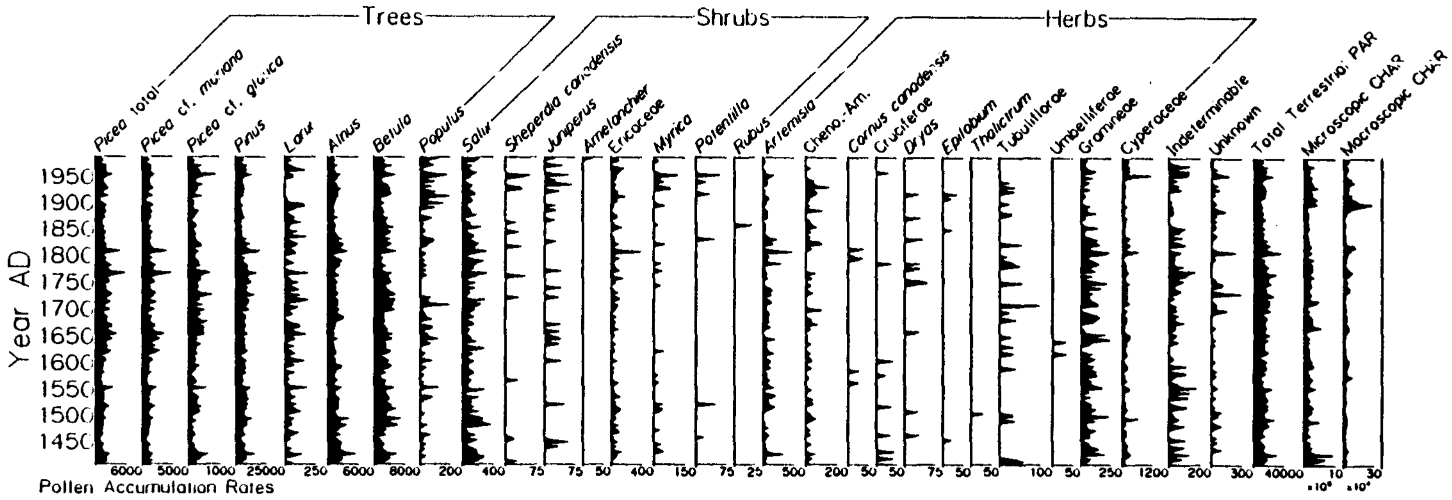

Figure5.4. Pollen accumulation rate diagram of terrestrial taxa in Fariya Lake. Pollen accumulation rates (PARs) are measured in pollen grains/cm^2 yr. Charcoal accumulation rates (CHARs) are measured in μm^2/cm^2 yr.

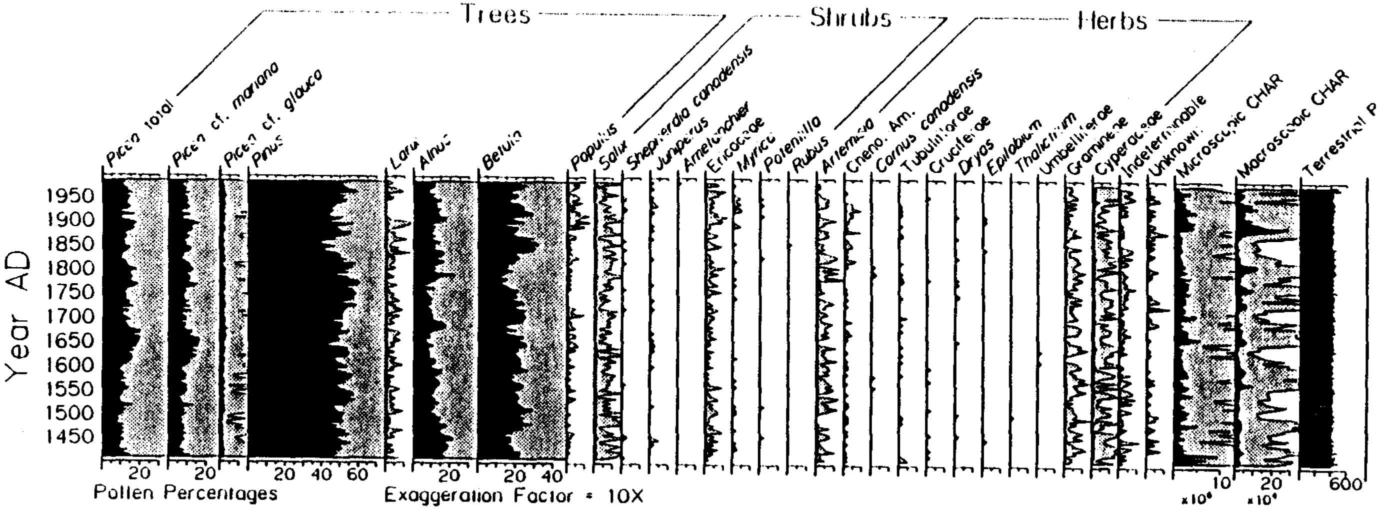

Figure 5.5. Pollen percentage diagram of terrestrial taxa in Fariya Lake. Charcoal accumulation rates (CHARs) are measured in $\mu m^2/cm^2$ yr.

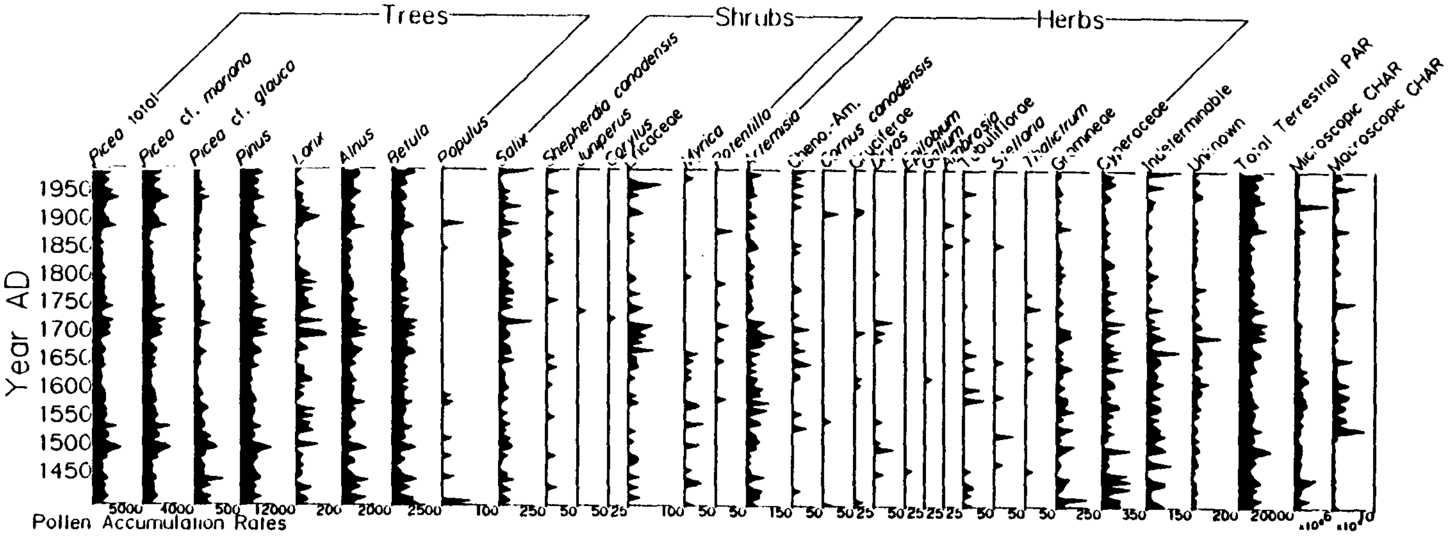

Figure 5.6. Pollen accumulation rate diagram of terrestrial taxa in Ninisith Lake. Pollen accumulation rates (PARs) are measured in pollen grains/cm^2 yr. Charcoal accumulation rates (CHARs) are measured in µm^2/cm^2 yr.

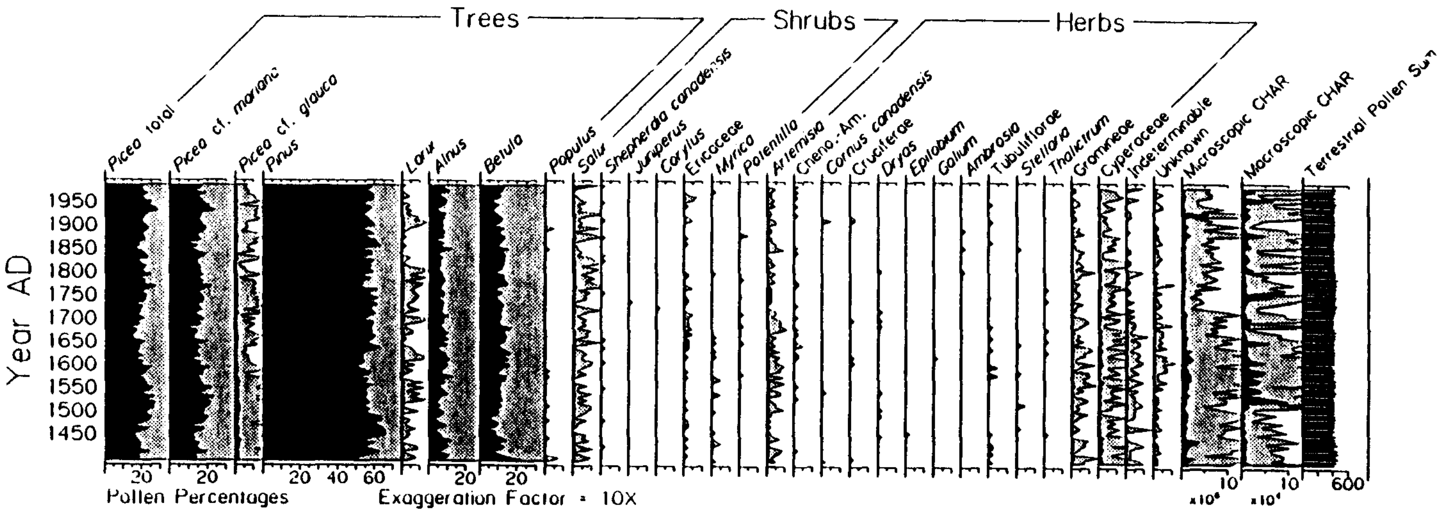

Figure 5.7. Pollen percentage diagram of terrestrial taxa in Ninisith Lake. Charcoal accumulation rates (CHARs) are measured in $\mu m^2/cm^2$ yr.

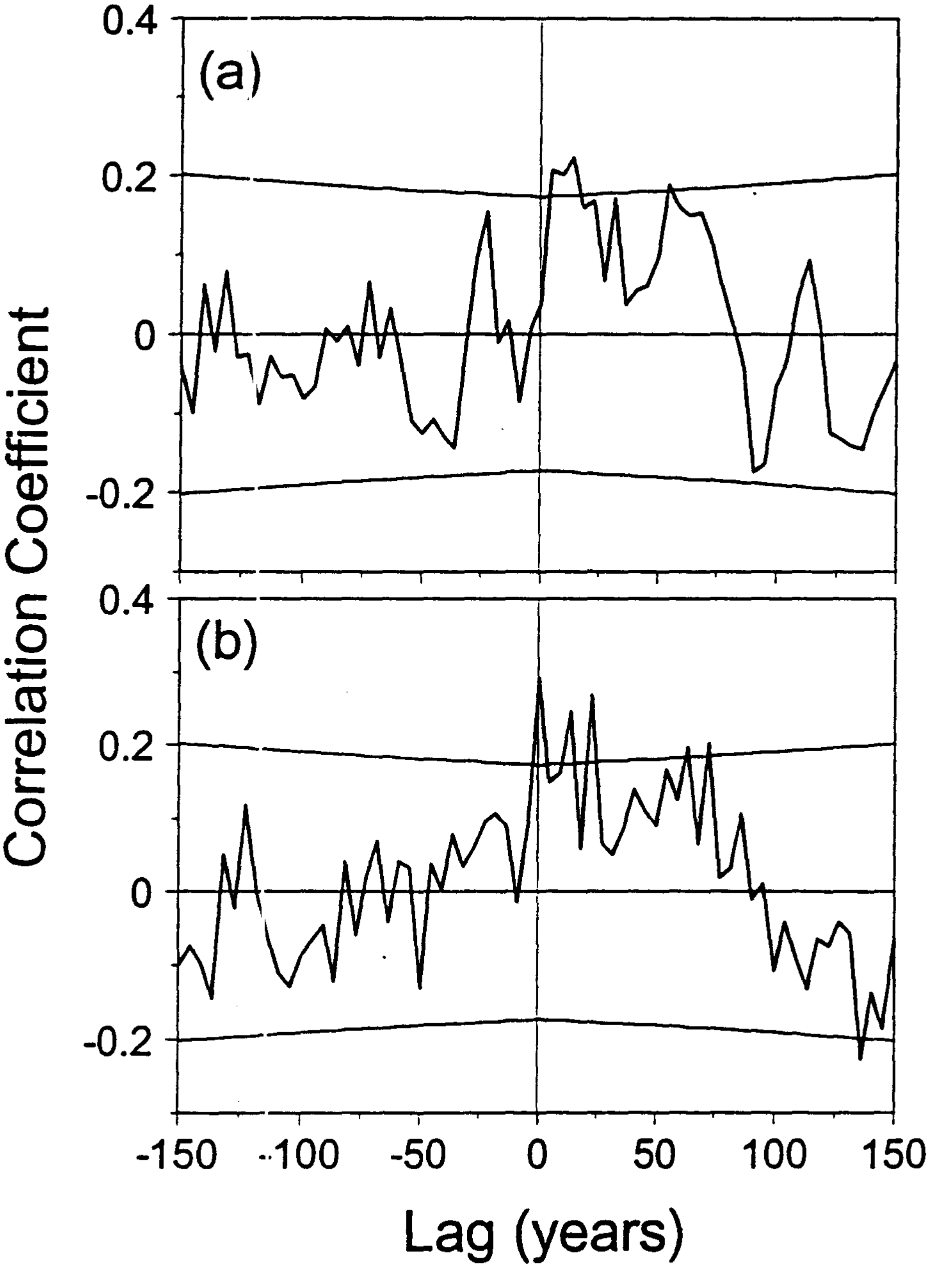

Figure 5.8. Cross correlation results from Fariya Lake of (a) Gramineae percentages vs. *Pinus* percentages and (b) Gramineae PARs vs *Pinus* PARs. The lag indicates the number of years that a peak in Gramineae lags a peak in *Pinus*. Horizontal lines are the 95% confidence limits.

Fire scars on trees around Fariya Lake record local fire events at 1943, 1906 and 1844, with tree age data indicating pulses of tree establishment following each of these fires (Fig. 5.9). A total of 10 palaeo-fires with a mean fire interval (MFI) of 56 years are indicated at Fariya Lake by peaks in macroscopic charcoal that are coincident with declines in *Pinus* PARs or percentages (Fig. 5.9). Six of the 10 palaeo-fires exhibit declines in both *Pinus* PARs and percentages, and 9 of the 10 palaeo-fires exhibit coincident increases in both Gramineae PARs and percentages. The two most recent palaeo-fires each occur within 5 years of the local fire events at 1943 and 1906 recorded by fire scars. The mean waterbreak distance (MWD) around Fariya Lake was 1.1 km.

Fire scars on trees around Ninisith Lake record local fire events at 1938, 1930, 1922, 1914 and 1878, with tree age data indicating a large pulse of tree establishment prior to the 1878 fire, a small pulse of tree establishment after the 1878 fire and a large pulse of tree establishment occurred as a result of the series of four fires in 1914, 1922, 1930 and 1938 (Fig. 5.10). A total of 9 palaeo-fires with a MFI of 51 years are indicated at Ninisith Lake by peaks in macroscopic charcoal that are coincident with declines in *Picea* cf. *mariana* PARs or percentages (Fig. 5.10). Six of the palaeo-fires exhibit declines in both *Picea* cf. *mariana* PARs and percentages. The two most recent palaeo-fires occur within 12 years of the extensive local fire events at 1930 and 1878 recorded by fire scars. The MWD around Ninisith Lake was 4.1 km.

A peak in microscopic charcoal in the Fariya Lake record coincides with 1 of the 3 dendrochronologically known local fires (Fig. 5.9), and peaks in microscopic

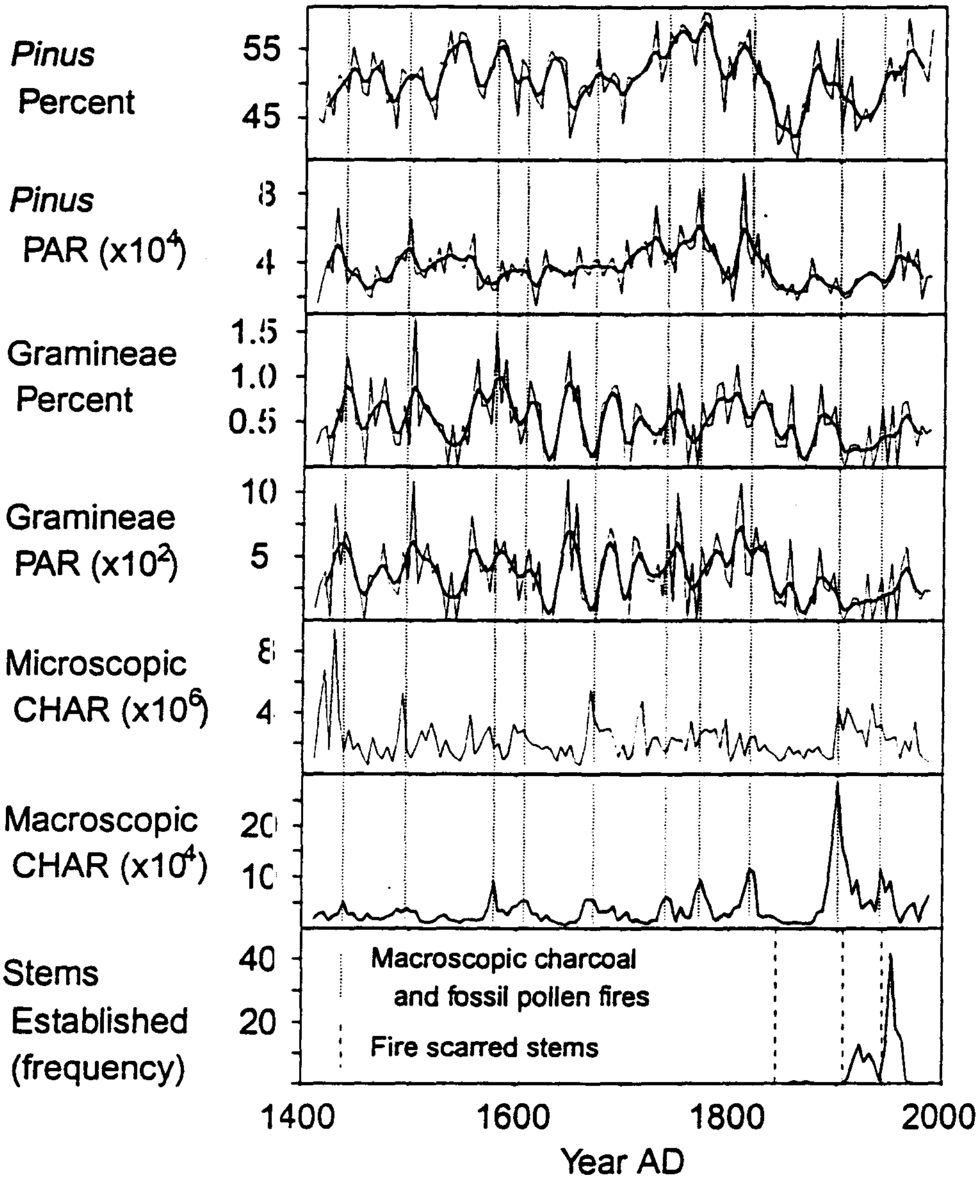

Figure 5.9. Macroscopic charcoal and fossil pollen inferred records of palaeo-fires over the past 600 years at Fariya Lake. Pollen accumulation rates (PARs) are measured in pollen grains/cm^2 yr and charcoal accumulation rates (CHARs) are measured in $\mu m^2/cm^2$ yr. The thin trace in the fossil pollen diagrams is the raw data and the thick trace presents the data smoothed with a 5 term binomial filter. Stem establishment is in 5 year age classes.

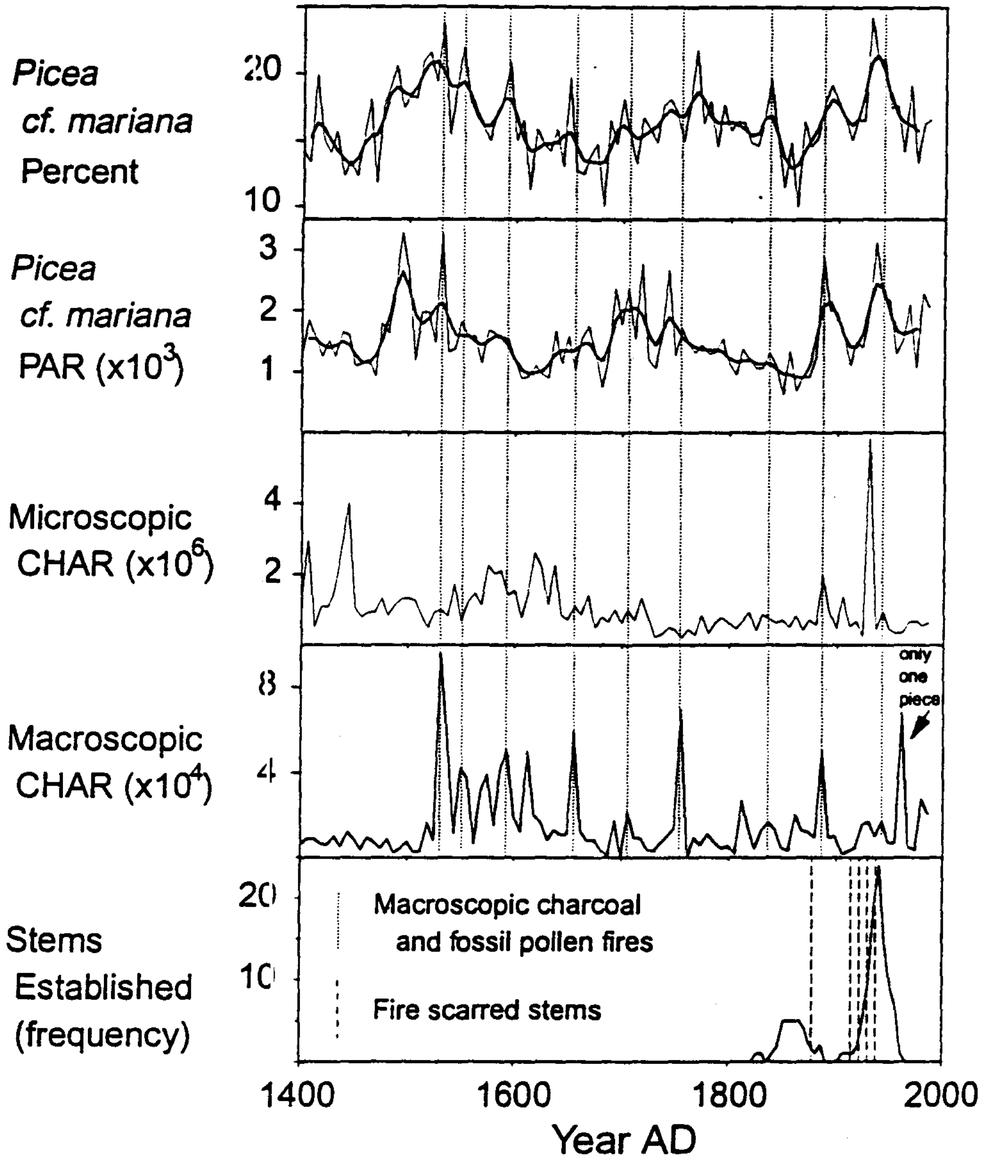

Figure 5.10. Macroscopic charcoal and fossil pollen inferred records of palaeo-fires over the past 600 years at Ninisith Lake. Pollen accumulation rates (PARs) are measured in pollen grains/cm^2 yr and charcoal accumulation rates (CHARs) are measured in µm^2/cm^2 yr. The thin trace in the fossil pollen diagrams is the raw data and the thick trace presents the data smoothed with a 5 term binomial filter. Stem establishment is in 5 year age classes.

charcoal in the Ninisith Lake record coincide with 2 of the 5 dendrochronologically known local fires. The microscopic and macroscopic charcoal records from Fariya Lake are significantly correlated (r_s = .32, p < .001), while the microscopic and macroscopic charcoal records from Ninisith Lake are not significantly correlated. (r_s = .19, p > .05). Spearman correlations were used because the macroscopic charcoal records are not normally distributed. The large peaks in microscopic charcoal from both lakes were rarely coincident with pollen indicators of palaeo-fires (Figs. 5.9 and 5.10).

The MFI of 56 years at Fariya Lake is midway between the regional fire cycle of 39 years found in jack pine forests and the regional fire cycle of 81 years for sites with a similar MWD of 0.00 to 2.99 km (Chapter 4). The MFI of 51 years at Ninisith Lake is higher than both the regional fire cycle of 78 years found in black spruce forests and the 60 year regional fire cycle found in sites with a similar MWD of 3.00 to 5.99 km.

5.5 DISCUSSION

5.5.1 Pollen evidence of succession

The hypothesis that the fossil pollen records exhibit post-fire vegetation successional patterns was weakly supported by the cross-correlation analysis of the Fariya Lake records and not supported by the analysis of the Ninisith Lake records. The observation that the Gramineae record from Fariya Lake was the only pollen taxon that exhibited cross-correlation results indicative of post-fire vegetation succession can be explained by several factors. Firstly, chronosequence studies from the North American boreal forest have typically found little or no successional changes in the abundance of ground layer vascular herbs and shrubs in jack pine and black spruce forests following (eg. Maikawa and Kershaw 1976, Carleton and Maycock 1980, Johnson 1981, Carroll and Bliss 1982, Jaseniuk and Johnson 1982, Foster 1985). Indeed, results have been quite contradictory with some studies finding continuous post-fire increases in the species richness of the ground layer vascular herbs and shrubs (eg. Foote 1983, Purchase and LaRoi 1983), and other studies finding continuous post-fire decreases in the species richness (eg. MacLean and Wein 1977, DeGrandpre et al. 1993). Secondly, those taxa which do exhibit successional changes in abundance are primarily insect pollinated (eg. *Epilobium angustifolium*, *Ledum groenlandicum* and *Vaccinium vitis-idaea*) and are therefore poorly represented in the fossil pollen records.

A third reason for the lack of significant results may be a lack of a consistent temporal resolution. Although each sample is 2.5 mm thick, the number of years contained in each sample can vary, and therefore so will the pollen content. This problem is apparent in the PAR records from both lakes as individual samples which exhibit prominent peaks in most taxa (Figs. 5.4 and 5.6). This problem is also evident in the cross-correlation results determined using the PAR records, as a peak correlation at year 0 which is displayed by most taxa (not shown). This problem with cross-correlation analyses using PAR data from massive sediments is also evident in the results of other studies (eg. Green 1981, Dodson 1990). The cross-correlation results from the pollen percentages are not adequate on their own because the multi-collinear nature of the pollen percentage makes the record of a taxa prone to variation without changes in its actual pollen production. For example, reductions in the amount of pollen from the locally dominant tree might result in increases in the pollen percentages from other taxa without coincident changes in their local abundance, which might then result in spuriously significant cross-correlations.

5.5.2 Evidence of local fires

The hypothesis that the coincidence of peaks in macroscopic charcoal and declines in pollen from the dominant local tree taxa would indicate the most recent local fires known from fire scars on local trees is generally supported by the results from both the Fariya and Ninisith Lake records.

At Fariya lake the two most prominent peaks in the charcoal record appear to coincide with the fire scars at 1943 and 1906, while the pollen evidence for these two fires is relatively weak. This is in contrast to the other 8 palaeo-fires inferred from the Fariya Lake records where the peaks in macroscopic charcoal are smaller though still prominent, but all of the peaks are confirmed by post-fire peaks in both Gramineae PARs and percents and five of the peaks are confirmed by post-fire declines in both *Pinus* PARs and percents. That the timing of the palaeo-fires marked at 1941 and 1901 is within five years of the fire scars at 1943 and 1906 suggests that the chronological control is good. The difference of 25 years between the palaeo-fire inferred at 1819 and the fire scar at 1844 may indicate some problems with the chronology. Alternatively, it may reflect the possibility that the 1819 fire left no fire scar evidence, and the 1844 fire scar was the result of a small fire. It should be noted that there are seven other peaks in both Gramineae PARs and percents, three of these also having coincident declines in both *Pinus* PARs and percents, for which there are no corresponding peaks in macroscopic charcoal.

At Ninisith Lake, although fire scars record four local fires between 1914 and 1938, only one palaeo-fire at 1942 was apparent during the 20th century portion of the fossil pollen and macroscopic charcoal records. The inability to record fires with such short intervals is not unexpected given that the Ninisith Lake record has a resolution of ~6.2 years. It should also be noted, though, that fire scars from only the 1922 and 1930 fires fire were found in more than one site, suggesting that the other two fires may have been very small. The palaeo-fire inferred at 1886 is within 8 years of the fire scar record at 1878, and the palaeo-fire marked at 1836 is confirmed by a subsequent pulse of tree establishment. These results suggest that the chronology is good. Although the 1886 palaeo-fire exhibits only a small peak in macroscopic charcoal, it exhibits strong declines in *Picea* cf. *mariana* PARs and percents. This underscores the value of using both macroscopic charcoal and pollen as indicators of palaeo-fires. It should be noted that three of the palaeo-fires exhibit only small macroscopic charcoal peaks, while three prominent macroscopic charcoal peaks do not have confirmatory fossil pollen evidence of fires.

The size of macroscopic charcoal peaks observed in both the Ninisith and Fariya Lake records will be affected by factors such as the size and proximity of a fire, the amount and type of fuel burned, the relative humidity and wind direction during the burn, and whether the fire was a heading or backing fire (Nelson and Ward 1980, Chandler et al. 1983). For example, a backing fire or a smoldering fire burning under high humidity and low wind conditions should produce large amounts of macroscopic charcoal, while a high intensity fire burning under hot, dry and windy conditions will combust fuel very efficiently and could produce a only a small peak in macroscopic charcoal. The occurrence of macroscopic charcoal peaks in Ninisith Lake without coincident declines in *Picea* cf. *mariana* pollen could be the result of factors affecting charcoal transport. For example, peaks could result from delayed erosion of charcoal from within the Ninisith Lake drainage basin. This might not happen in the smaller and steeper Fariya Lake drainage basin.

Despite these problems with the macroscopic charcoal record, it is notable that peaks in microscopic charcoal exhibit even less coincidence with fire scar records and fossil pollen indicators of palaeo-fires (Figs. 5.9 and 5.10). This observation reflects the large regional source area of small, light microscopic charcoal (eg. Clark 1988, MacDonald et al. 1991). The weak correlation between microscopic and macroscopic charcoal at Fariya Lake, and the non-significant correlation between microscopic and macroscopic charcoal at Ninisith Lake, indicates that the microscopic charcoal cannot be used as a proxy for macroscopic charcoal.

In both the Fariya and Ninisith Lake records, the lack of perfect coincidence between the various pollen indicators of palaeo-fires, and between them and the macroscopic charcoal records, could be the result of the pollen records being affected by factors such as the size, contiguity, intensity and season of the burn. For example, a large fire could cause a large decline in pollen from the dominant local taxa if only the dominant local taxon was burned, but could lead to a more equivocal response if most of the area burned was dominated by a taxa different from the local dominant. Also, a large regional fire might affect changes in the record of the light and easily transported pollen, but not cause a peak in the heavy and poorly transported macroscopic charcoal. In addition, if a fire is not very intense then it will not burn all of the vegetation but could produce a large charcoal peak. The fire marked at 1941 in the Fariya Lake sediments might be an example of such an event. This palaeo-fire exhibits a large macroscopic charcoal peak, but no large change in *Pinus* pollen percentages. The 1943 fire, which it is assumed this palaeo-fire represents, was extensive but did not kill all of the jack pine stems at most sites. The equivocal nature of the pollen record of fires is similar to that found in other studies using both massive and laminated lake sediments (eg. Swain 1973, 1980, Cwynar 1978, Patterson and Backman 1988).

It should be noted that the fossil pollen and charcoal records in Fariya and Ninisith Lakes have, as have all massive lake sediments, been altered by sediment mixing. Based on their surface area, maximum depths and published heuristics that relate these parameters to the type of sediment mixing (Larsen and MacDonald 1993), the types of mixing present in Fariya and Ninisith Lakes can be predicted (Fig. 5.11). It is expected that the Ninisith Lake sediments should be mixed more frequently than those in Fariya Lake. Increased sediment mixing would reduce the amount of long

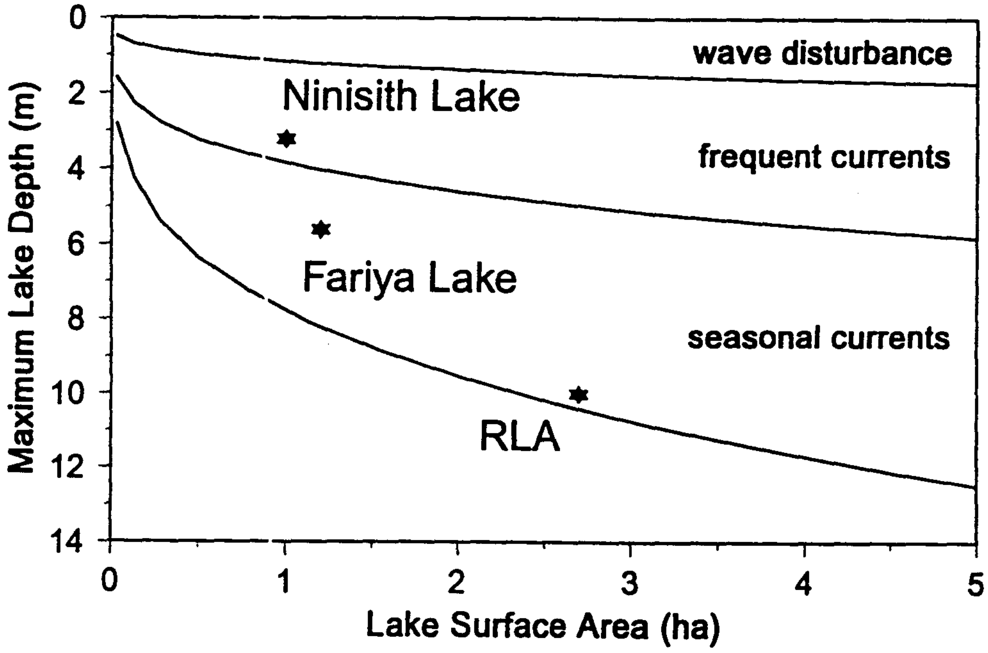

Figure 5.11. The types of sediment mixing expected within Ninisith Lake, Fariya Lake and varved RLA based on lake surface area, maximum lake depth and heuristics given in Larsen and MacDonald (1993). The types of mixing present in deep lakes are also present in shallower lakes. It is therefore expected that Ninisith Lake sediments would be disturbed by both seasonal and frequent currents while Fariya Lake sediments would be disturbed only by seasonal currents.

term variation in the fossil records and could potentially, if the amount of mixing is variable through time, introduce additional short term variation. Temporal variations in mixing rates could be caused by the removal of vegetation around the site following afire, which would increase the wind speeds along the lake surface and therefore the strength of currents within the lake. This may explain why the Ninisith Lake fossil pollen and charcoal records appear to exhibit less variation at the 50-100 year scale and more variation at the 5-50 year scale than do the Fariya Lake records.

5.5.3 Mean fire interval estimates

The hypothesis that the palaeo- mean fire interval (MFI) estimates would be the same as the fire cyle estimate obtained from regional scale dendrochronological records was supported at Fariya Lake and was not supported at Ninisith Lake.

The observation that the palaeo-MFI estimate of 56 years at Fariya Lake was midway between the regional fire cycle estimates of 39 years found in sites dominated by jack pine and 81 years found in sites with a similar mean waterbreak distance (MWD) of 0.00 to 2.99 km likely reflects the fact that both of these factors affect fire frequency (Chapter 4). The 1.1 km MWD at Fariya Lake is much less than the 7.2 km MWD found in a sample of regional jack pine forests (Chapter 4). It is therefore likely that the small MWD at Fariya Lake reduces the spread of fires into the drainage basin relative to that in other jack pine sites, leading to a MFI that is lower than that typically found in regional jack pine forests. Note that the high fire frequency in jack pine forests likely occurs because these forests typically occur in dry sites which have low soil water storage, and the vegetation therefore becomes drier and more flammable than does vegetation in wetter sites.

The observation that the palaeo-MFI estimate of 51 years at Ninisith Lake was higher than both the regional fire cycle estimates of 78 years found in sites dominated by black spruce and 60 years found in sites with a similar MWD of 3.00-5.99 km likely indicates the poor quality of the palaeo-MFI estimate. Since the 4.1 km MWD at Ninisith Lake is very similar to the 4.3 km MWD found in a sample of regional black spruce forest sites (Chapter 4), a combination of vegetation and MWD cannot explain the discrepancy as it did at Fariya Lake. Indeed, it is surprising that the MFI is higher than expected given that some known local fires were not evident in the fossil record. It is possible that the regional fire cycle estimate for black spruce is too slow, but it is actually faster than the 100 year fire cycle estimate for black spruce forests in Alaska (Yarie 1981). It is also possible that the relatively high MFI observed at Ninisth Lake is due to the large amounts of jack pine forest in the area leading to greater fire spread into the lake basin. Alternatively, the high MFI could reflect incorrect inference of some palaeo-fires. In Ninisith Lake the small size of some macroscopic charcoal peaks, the presence of only one pollen taxa to indicate fires, the drainage basin characteristics and the high degree of mixing present in the sediments are all likely sources of noise in the data that could lead to such false inferences.

The results from Fariya and Ninisith Lakes suggest that fine resolution fossil pollen and macroscopic charcoal analyses of massive lake sediments can provide useful data for estimating variations in fire frequency related to differences in vegetation and environmental conditions. However, the results indicate that to obtain good evidence of palaeo-fires, studies should use lakes with the following characteristics: the lakes should be deep enough that sediments are infrequently mixed, the locally dominant forest type should exhibit a clear successional pattern that involves wind pollinated taxa, and this forest type should extend at least one kilometre around the lake.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

6.1 SUMMARY OF RESULTS AND HYPOTHESIS TESTS

The objectives of this study were to estimate the mean fire frequency of the boreal forest of northern Alberta, and to investigate whether the fire frequency varies in response to factors that are known to affect fire behaviour. To address these objectives, four hypotheses were developed and tested. The results of the studies used to test these hypotheses, and the status of each hypothesis, are presented below.

1) Tree ring-width records from the boreal forest provide a proxy record of climate.

To test this hypothesis ring-width chronologies were constructed from three white spruce (*Picea glauca* (Moench) Voss) and two jack pine (*Pinus banksiana* Lamb.) sites in the boreal forest of northern Alberta. I examined whether these chronologies could provide proxy records of climate variation, fire weather and annual area burned, and whether the chronologies were effected by outbreaks of spruce budworm (*Choristoneura fumiferana* (Clem.)). All chronologies exhibited significant positive correlations with June precipitation in the growth year and two chronologies exhibited significant positive correlations with June precipitation in the prior year. The white spruce chronologies also exhibited significant negative correlations with November and May temperatures in the prior year.

All of the chronologies exhibited significant negative correlations with fire weather variables and annual area burned in Wood Buffalo National Park. The fire weather variables and annual area burned were, in general, most highly correlated with ring-widths in the following year. The white spruce chronologies displayed additional variance that might reflect three discrete spruce budworm outbreaks. The length of these inferred outbreaks ranged from 3 to 13 years. However, historical records of local spruce budworm outbreaks were not adequate to locally validate the dendrochronological method of inferring spruce budworm outbreaks, making these inferred outbreaks speculative. Although correlations between ring-widths, fire weather and annual area burned were high for the white spruce, the results suggest that care should be taken when interpreting short term patterns in white spruce chronologies from the central boreal forest because of the possible impact of spruce budworm activity. The hypothesis that tree ring width records from the boreal forest provide a good proxy record of climate was accepted.

2) Annual area burned in the boreal forest varies in response to climate changes.

To test this hypothesis I employed historical records of annual area burned from WBNP between 1950 and 1989, and dendrochronological records of the time since the last fire (TSLF) for 166 sites distributed throughout WBNP. These records of fire history were correlated with historical climate records from Fort Smith NWT and tree ring proxy records of climate and area burned from WBNP.

Annual area burned between 1950 and 1989 was negatively correlated with mean fire-season precipitation and annual tree ring-width indices from 5 stands in WBNP, and positively correlated with the fire-season means of temperature and fire weather. Life table estimates of semi-decadal variations in mean annual percent area burned were positively correlated with historical records of annual area burned in WBNP between 1950 and 1989 and significantly negatively correlated with tree ring-width indices from 5 stands in WBNP between 1850 and 1989. Analysis was restricted to the post- 1850 time period because there were very few samples prior to that time. Peaks in annual area burned and semi-decadal estimates of mean annual percent area burned appear to be episodic, with an average interval of 30 to 40 years.

The cumulative TSLF distribution was analyzed using logarithmic regression to determine if there was a change in fire frequency at the end of the Little Ice Age (mid 19th c.). A significant change in slope was apparent in the TSLF distributions for all of WBNP, the black spruce dominated stands, and the near and medium mean waterbreak distance classes. The fire cycle estimates for these groups were all significantly higher during the period 1750 to 1859 (fire cycle = 25 to 49 years) than they were the 1860 to 1989 period (fire cycle = 59 to 89 years). It was suggested that this post-Little Ice Age decrease in fire frequency could reflect an increase in precipitation or a change in aboriginal burning practices. The lack of a long term (~300 year) local climate record does not allow these alternative explanations to be disproven.

The results of these tests all support the hypothesis that annual area burned in the boreal forest varies in response to climate change.

3) Boreal forest fire frequency varies with differences in forest type and the proximity to waterbreaks.

To test this hypothesis the dendrochronological records of TSLF from 166 sites distributed throughout WBNP were disaggregated into vegetation and mean waterbreak distance classes and analyzed using survival models. The fire cycles (the time required to burn an area equal to the entire study area) in jack pine (39 years) and aspen forests (39 years) were significantly higher than those in black spruce (78 years) and white spruce forests (96 years). These estimates are similar to those obtained in other studies from the boreal forest of North America, but build on them by showing statistically significant differences. TSLF was also found to be significantly related to the mean distance to waterbreaks, and the mean distance to waterbreaks was significantly higher in jack pine and aspen forests than in black or white spruce forests. It was suggested that the variations in fire frequency by vegetation type are related to these differences in the mean distance to waterbreaks as well as factors such as differences in soil moisture availability in the typical sites within which the different vegetation types are found. These results support the hypothesis that fire frequency varies with differences in forest type and the proximity of waterbreaks.

4) Fossil pollen and macroscopic charcoal records from massive lake sediments can provide meaningful estimates of local fire frequency.

To test this hypothesis six hundred year records of fire history were reconstructed from the non-laminated sediments of two lakes in the boreal forest of northern Alberta using fine resolution fossil pollen and macroscopic charcoal analysis. Fariya Lake is surrounded by jack pine forest and Ninisith Lake is surrounded by black spruce forest. Contiguous ~4.6 year samples were analyzed from Fariya Lake and contiguous ~6.3 year samples were analyzed from Ninisith Lake. In addition, dendrochronological analyses were used to reconstruct the timing of fires which occurred around the lakes over the past 150 years.

The pollen records from each lake were examined for post-fire vegetation succession using cross-correlation analyses between the locally dominant tree and other taxa. Significant cross-correlations were only found at Fariya Lake where peaks in Gramineae followed peaks in *Pinus*. Peaks in macroscopic charcoal coupled with declines in the pollen records of the locally dominant tree taxa coincided with the two most recent local fires around Fariya Lake which are evident in the local tree ring records, and 2 of the 5 most recent fires around Ninisith Lake which are evident in the local tree ring records. Some of the known local fires around Ninisith Lake were likely too small in size and occurred too frequently in time to be resolved in the lake fossil record.

A total of 10 large fires, with a mean fire interval of 56 years, were detected in the Fariya Lake record. A total of 9 large fires, with a mean fire interval of 51 years, were detected in the Ninisith Lake record. These mean fire intervals were compared to regional mean fire interval estimates obtained from a dendrochronological fire history analysis of an adjacent 44,807 km^2 area. In this dendrochronological study the fire frequency was found to be related to both vegetation type and the mean distance to mapped waterbodies around the site which could stop the spread of a fire. The 56 year mean interval between palaeo-fires observed at Fariya Lake was between the regional mean fire cycle estimates of 39 years found in sites dominated by jack pine and of 81 years found in sites with a similar mean waterbreak distance (MWD) of 0.00 to 2.99 km. The 51 year mean interval between observed palaeo-fires at Ninisith Lake was higher than the both the regional mean fire cycle estimates of 78 years found in sites dominated by black spruce and of 60 years found in sites with a similar MWD of 3.00-5.99 km. This unexpectedly high mean fire interval estimate appears to be the result of a noisy fossil record which occurs because the lake is shallow and therefore experiences high rates of sediment mixing, and because jack pine forests that occur close to the lake likely influence the fossil pollen record.

These results therefore support the hypothesis that, given certain conditions, fossils of pollen and macroscopic charcoal contained in massive lake sediments can provide meaningful records of fire frequency.

6.2 CONCLUSIONS AND SUGGESTIONS

The results of this study, in combination with previous research on boreal forest fires, allow several conclusions to be reached regarding fire in the boreal forest. In addition, I suggest future research that might further improve our knowledge of boreal forest fire frequency.

1) The finding that area burned in WBNP varies at the annual, decadal and centennial scales is valuable for several reasons. First, it suggests that care should be used when estimating fire frequency from historical records. For example, it is possible that the recent reductions in fire frequency observed in some studies of historical records, and suggested to possibly be due to fire suppression (eg. Barney and Stocks 1983), may simply reflect climate driven varations in area burned. Dendrochronological fire history methods such as used in this study could be used to test the hypothesis that fire frequency has been reduced in certain areas due to climate variation rather than fire suppression.

Second, the finding that area burned varies at the annual, decadal and centennial scales is important for long term fire management. Since these variations in area burned are linked to climate, it is likely that they are being driven by climatic mechanisms that operate at different temporal scales. For fire managers to obtain good predictions of future area burned (eg. Fujioka 1991, Flannigan and Van Wagner 1991), the climate models they use should attempt to incorporate these different temporal scales of fire - climate interaction.

Third, the finding that decadal scale variations in the number of stands in different time since last fire (TSLF) classes in WBNP appears to be due to decadal scale variations in climate supports the similar contentions made in other boreal fire history studies (eg. Rowe et al. 1974, Foster 1983, Bergeron and Archambault 1993). It would be profitable to analyze the data from these other studies using the life table methods used in this study. Such analyses might provide records of whether decadal scale fire frequency variations are synchronous at the continental scale.

2) The finding that fire frequency varies with vegetation type and mean waterbreak distance is valuable for several reasons. First, it supports the similar contentions made in previous studies that were not backed up with proper statistical analyses. Second, that these spatial variations in fire frequency were larger than were the temporal variations at the centennial scale indicates that they are important to recognize in fire management with fire observation towers perhaps being concentrated in areas with higher fire frequency. The spatial variations in fire frequency are also important for ecosystem studies since nutrient cycles may be more rapid in areas with higher fire frequency. Third, these spatial variations in fire frequency should be taken into account in models of forest change due to global warming (eg. Antonovski et al. 1992, Rizzo and Wiken 1992), since areas with higher fire frequency should be sites in which forest change may occur most rapidly.

Although spatial variations in fire frequency have been related to differences in vegetation and mean waterbreak density, mechanistic reasons for these relations have not been proven. I raised the hypotheses that these variations occur because fire frequency is higher in sites on dry than on wet soils, and that it is higher in sites where there are fewer waterbodies that will slow fire spread. Fire behaviour studies designed in a manner that could test these hypotheses would be valuable in developing the relations suggested here into a form that would allow spatial modelling at the mechanistic level.

3) The finding that fire frequency can be estimated from fossil pollen and macroscopic charcoal from massive lake sediments is valuable since lakes with massive sediments are much more common than those with annually laminated sediments. As a result, lakes with massive sediments could be used to address a number of questions regarding fire frequency that reliance on lakes with laminated sediments would disallow in all but a few cases. For example, analysis of fossils in massive sediments could be used to determine the palaeo- fire frequency in areas where the forest has been disturbed by logging or fire suppression. In addition, analysis of fossils in massive sediments it could be used to determine if fire frequency varies along environmental gradients, such as soil moisture or mean waterbreak density, expected to be related to fire frequency.

The results also indicate that, for fossil pollen and macroscopic charcoal records from massive sediments to provide useful palaeo fire frequency estimates, the lake sediments must not be frequently mixed and that vegetation should be relatively homogenous approximately one kilometre around the lake.

APPENDIX

DATA AVAILABILITY

The tree ring chronologies, forest age and fossil pollen and charcoal data analyzed in this research are available from three sources. The tree ring chronologies and fossil pollen and charcoal data will be sent, following publication of data analyses in a refereed journal, to two international data banks that allow free access to the data for all contributors and other interested researchers. The forest age data was gathered under contract K2585-C9-014 to the Canadian Park Service and therefore belongs to them. I will provide the data to any researcher if access is approved by the Canadian Parks Service.

Pollen data

North American Pollen Database
Illinois State Museum
1011 East Ash
Springfield, Illinois 62703
USA

Tree-ring data

International Tree-Ring Data Bank
Laboratory of Tree-Ring Research

University of Arizona

Tucson, Arizona 85721

USA

Forest age data

Wood Buffalo National Park

P.O. Box 750

Fort Smith NWT

X0E 0P0

Canada

REFERENCES

Airphoto Analysis Associates. 1979. Biophysical resource inventory of Wood Buffalo National Park. Parks Canada, Winnipeg, Manitoba.

Antonovski, M.Ya., TerMikaelian, M.T., and Furyaev, V.V. 1992. A spatial model of long-term forest fire dynamics and its applications to forests in western Siberia. In A Systems Analysis of the Global Boreal Forest. Edited by H.H. Shugart, R. Leemans, G.B. Bonan. Cambridge University Press, Cambridge. pp. 373-403.

Archambault. S. and Bergeron, Y. 1992. An 802-year tree-ring chronology from the Quebec boreal forest. Canadian Journal of Forest Research 22: 674-682.

Arno, S.F. and Sneck, K.M. 1977. A method for determining fire history in coniferous forests of the Mountain West. United States Department of Agriculture Forest Service General Technical Report INT-42.

Arquilliere. S., Filion, L., Gajewski, K. and Cloutier, C. 1990. A dendroecological analysis of eastern larch (Larix laracina) in subarctic Quebec. Canadian Journal of Forest Research 20:1312 - 1319.

Auclair, A.N.D. and Carter, T.B. 1993. Forest wildfires as a recent source of CO_2 at northern latitudes. Canadian Journal of Forest Research 23: 1528-1536.

Balling, R.C. Jr., Meyer, G.A., and Wells, S.G. 1992. Relation of surface climate and area burned in Yellowstone National Park. Agricultural and Forest Meteorology 60: 285-293.

Barney, R.J. and Stocks, B.J. 1983. Fire frequencies during the suppression period. In The Role of Fire in Northern Circumpolar Ecosystems. Edited by Wein, R.W. and MacLean, D.A., John Wiley & Sons Ltd. New York. pp. 45 - 62.

Bayley, S.E., Schindler, D.W., Keaty, K.G., Parker, B.P., and Stainton, M.P. 1992. Effects of multiple fires on nutrient yields from streams draining boreal forest and fen watersheds: nitrogen and phosphorous. Canadian Journals of Fisheries and AquaticScience 49: 584-596.

Bendell, J.F. 1974. Effects of fire on birds and mammals. In Fire and ecosystems. Edited by T.T. Kozlowski and C.E. Ahlgren. Academic Press, New York. pp. 73-138.

Bergeron, Y. 1991. The influence of island and mainland lakeshore landscapes on boreal forest fire regimes. Ecology 72: 1980-1992.

Bergeron, Y. and Archambault, S. 1993. Decreasing frequency of forest fires in the southern boreal zone of Quebec and its relation to global warming since the end of the 'Little Ice Age'. The Holocene 3: 255-259.

Blais, J.R. 1954. The recurrence of spruce budworm infestations in the past century in the Lac Seul area of northwestern Ontario. Ecology 35: 62 - 71.

Blais, J.R. 1962. Collection and analysis of radial growth data from trees for evidence of past spruce budworm outbreaks. Forestry Chronicle 38: 474 - 484.

Blais, J.R. 1983. Trends in the frequency, extent and severity of spruce budworm outbreaks in eastern Canada. Canadian Journal of Forest Research 13: 539 - 547.

Blasing, T.J., Solomon, A.M., and Duvick, D.N. Response functions revisited. Tree-Ring Bulletin 44: 1 - 15.

Briffa, K.R. and Cook, E.R. 1989. Methods of response function analysis. In Methods of dendrochonology. Edited by Cook, E.R. and Kairiukstis, L.A. Kluwer, Dordrecht. pp. 240 - 247.

Briffa, K.R., Jones, P.D., Bartholin, T.S., Eckstein, D., Schweingruber, F.H., Karlen, W., Zetterberg, P., and Eronen, M. 1992. Fennoscandian summers from AD 500: temperature changes on short and long timescales. Climate Dynamics 7: 111 - 119.

Buxton, G.F., Cyr, D.R., Dumbroff, E.B. and Webb, D.P. 1985. Physiological responses of three northern conifers to rapid and slow induction of moisture stress. Canadian Journal of Forest Research 63: 1171- 1176.

Canada Department of Fisheries and Forestry. 1969. Annual Report on the Forest Insect and Disease Surveys. Forestry Branch. Ottawa.

Carleton, T.J. and MayCock, P.F. 1978. Dynamics of the boreal forest south of James Bay. Canadian Journal of Botany 56: 1157-1173.

Carleton, T.J. and Maycock, P.F. 1980. Vegetation of the boreal forests south of James Bay: non-centered component analysis of the vascular flora. Ecology 61: 1199-1212.

Carroll, S.B. and Bliss, L.C. 1982. Jack pine - lichen woodland on sandy soils in northern Saskatchewan and northeastern Alberta. Canadian Journal of Botany 60: 2270-2282.

Chandler, C., Cheney, P., Thomas, P., Trabaud, L. and Williams, D. 1983. Fire in forestry. Volume 1. Forest fire behavior and effects. John Wiley & Sons, New York.

Clark, J.S. 1988. Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. Quaternary Research 30: 67-80.

Clark, J.S. 1989. Ecological disturbance as a renewal process: theory and application to fire history. Oikos 56: 17-30.

Clark, J.S. 1990.Fire and climate change during the last 750 years in northwestern Minnesota. Ecological Monographs 60: 135-159.

Clark, J.S., Merkt, J. and Muller, H. 1989. Post-glacial fire, vegetation, and human history on the northern alpine forelands, south-western Germany. Journal of Ecology 77:897-925.

Cogbill, C.V. 1985. Dynamics of boreal forests of the Laurentian Highlands, Canada. Canadian Journal of Forest Research 15: 252-261.

Cook, E.R. 1990. Bootstrap confidence intervals for red spruce ring-width chronologies and an assessment of age-related bias in recent growth trends. Canadian Journal of Forest Research 20: 1326 - 1331.

Cooper, W.S. 1913. The climax forest of Isle Royal, Lake Superior, and its development. Botanical Gazette 55: 1 - 44, 115 - 140, 189 - 235.

Crowley, T.J. and Kim, K-Y. 1993. Towards development of a strategy for determining the origin of decadal-centennial scale climate variability. Quaternary Science Reviews 12: 375-385.

Cwynar, L.C. 1978. Recent history of fire and vegetation from laminated sediments of Greenleaf Lake, Algonquin Park, Ontario. Canadian Journal of Botany 56: 10-21.

Dang, Q.L. and Lieffers, V.J. 1989. Climate and annual ring growth of black spruce in some Alberta peatlands. Canadian Journal of Botany 67: 1885 - 1889.

Dansereau, P-R. and Bergeron, Y. 1993. Fire history in the southern boreal forest of northwestern Quebec. Canadian Journal of Forest Research 23: 25-32.

Davis, K.P. 1959. Forest fire: control and use. McGraw-Hill, New York.

Dean, W.E. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. Journal of Sedimentary Petrology 44: 249-253.

DeGrandpre, L., Gagnon, D. and Bergeron, Y. 1993. Changes in the understorey of Canadian southern boreal forest after fire. Journal of Vegetation Science 4: 803-810.

Dix, R.L. and Swan, J.M.A. 1971. The roles of disturbance and succession in upland forest at Candle Lake, Saskatchewan. Canadian Journal of Botany 49: 657-676.

Dodson, J.R. 1990. Fine resolution pollen analysis of vegetation history in the Lough Adoon Valley, Co. Kerry, western Ireland. Review of Palaeobotany and Palynology 64: 235-245.

Eckstein, D., Hoogesteger, J., and Holmes, R.L. 1991. Insect-related differences in growth of birch and pine at northern treeline in Swedish Lapland. Holarctic Ecology 14: 18 - 23.

Engelmark, O., Kullman, L. and Bergeron, Y. 1994. Fire and age structure of Scots pine and Norway spruce in northern Sweden during the past 700 years. New Phytologist 126: 163-168.

Environment Canada. 1982. Canadian climate normals 1951-1980. Atmospheric Environment Service, Downsview, Ontario.

Faegri, K., Kaland, P.E., and Kryzywinski, K. 1989. Textbook of pollen analysis by Knut Faegri and Johs. Iversen, 4th Edition. John Wiley & Sons, Chichester, England.

Flannigan, M.D. and Harrington, J.B. 1988. A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada (1953-1980). Journal of Applied Meteorology 27: 441-452.

Flannigan, M.D. and Van Wagner, C.E. 1991. Climate change and wildfire in Canada. Canadian Journal of Forest Research 21: 66 - 72.

Flannigan, M.D. and Wotton, B.M. 1991. Lightning-ignited forest fires in northwestern Ontario. Candian Journal of Forest Research 21: 277-287.

Foote, M.J. 1983. Classification, description, and dynamics of plant communities after fire in the taiga of interior Alaska. United States of Agriculture Forest Service Research Paper PNW 307.

Forestry Canada. 1990. Selected forest statistics. Environment Canada, Forestry Canada Information ReportE-X-44.

Forestry Canada. 1992. Development and structure of the Canadian forest fire behaviour prediction system. Forestry Canada fire danger group Information Report ST-X-3. Forestry Canada, Ottawa.

Foster, D.R. 1983. The history and pattern of fire in the boreal forest of southeastern Labrador. Canadian Journal of Botany 61: 2459-2471.

Foster, D.R. 1985. Vegetation development following fire in *Picea mariana* (black spruce) - *Pleurozium* forests of south-eastern Labrador, Canada. Journal of Ecology 73: 517-534.

Fox, G.A. 1993. Failure-time analysis: emergence, flowering, survivorship, and other waiting times. In Design and Analysis of Ecological Experiments. Edited by S.M. Scheiner and J. Gurevitch. Chapman & Hall, New York. pp. 253-289.

Fox, J.F. 1989. Bias in estimating forest disturbance rates and tree lifetimes. Ecology 70: 1267-1272.

Franklin, S.E. 1993. Multispectal classification of fire fuel types and land cover classes in Wood Buffalo National Park using Landsat MSS digital imagery. Parks Canada Contract No. K3585-C2-002.

Fritts, H.C. 1976. Tree rings and climate. Academic Press, London.

Fritts, H.C. 1991. Reconstructing large-scale climatic patterns from tree-ring data. The University of Arizona Press, Tucson.

Fritts, H.C. 1993. PRECON 3.0 users manual. Laboratory of Tree-Ring Research, University of Arizona.

Fujioka, F.M. 1991. The art of long-range fire weather forecasting. In Fire and the environment: ecological and cultural perspectives. Edited by S.C. Nodvin and T.A. Waldrop. Southeastern Forest Experimental Station, Asheville NC.

Ghil, M. and Vautard, R. 1991. Interdecadal oscillations and the warming trend in global temperature time series. Nature 350: 324-327.

Gottman, J.M. 1981. Time-series analysis. Cambridge University Press, Cambridge, England.

Green, D.G. 1981. Time series and postglacial forest ecology. Quaternary Research 15: 265-277.

Greenbank, D.O. 1956. The role of climate and dispersal in the initiation of outbreaks of the spruce budworm in New Brunswick. Canadian Journal of Zoology 34: 453 - 476.

Gregory, R.A., and Wilson, B.F. 1968. A comparison of cambial activity of white spruce in Alaska and New England. Canadian Journal of Botany 46: 733-734.

Grissino-Mayer, H., Holmes, R., and Fritts, H. 1992. International tree-ring data bank program library manual. Laboratory of Tree-Ring Research, University of Arizona.

Hansen, B.C.S. and Engstrom, D.R. 1985. A comparison of numerical and qualitative methods of separating pollen of black and white spruce. Canadian Journal of Botany 63: 2159-2163.

Hare, F.K. and Thomas, M.K. 1979. Climate Canada. John Wiley & Sons, New York.

Harper, J.L. 1977. Population biology of plants. Academic Press, London.

Harrington, J.B., Flannigan, M.D. and Van Wagner, C.E. 1983. A study of the relation of components of the Fire Weather Index to monthly provincial area burned by wildfire in Canada, 1953 - 1980. Environment Canada, Canadian Forestry Service Information Report PI-X-25.

Heinselman, M.L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area. Quaternary Research 3: 329-382.

Houghton, J.T., Jenkins, G.J., and Ephraums, J.J. 1990. Climate change. Cambridge Univeristy Press, Cambridge.

Howarth, D.A. and Rogers, J.C. 1992. Problems associated with smoothing and filtering of geophysical time-series data. Physical Geography 13: 81-99.

Jacoby, G.C., and D'Arrigo, R.D. 1989. Reconstructed northern hemisphere annual temperature since 1671 based on high-latitude tree-ring data from North America. Climatic Change 14: 39 - 59.

Jaseniuk, M.A. and Johnson, E.A. 1982. Peatland vegetation organization and dynamics in the western subarctic, Northwest Territories, Canada. Canadian Journal of Botany 60: 2581-2593.

Johnson, E.A. 1979. Fire recurrence in the subarctic and its implications for vegetation composition. Canadian Journal of Botany 57: 1374-1379.

Johnson, E.A. 1981. Vegetation organization and dynamics of lichen woodland communities in the Northwest Territories, Canada. Ecology 62: 200-215

Johnson. E.A. and Fryer. G.I. 1989. Population dynamics in lodgepole pine - Engelman spruce forests. Ecology 70: 1335-1345.

Johnson, E.A., Fryer, G.I. and Heathcott, M.J. 1990. The influence of man and climate on frequency of fire in the interior wet belt forest, British Columbia. Journal of Ecology 78: 403-412.

Johnson, E.A. and Larsen, C.P.S. 1991. Climatically induced change in fire frequency in the southern Canadian Rockies. Ecology 72: 194-201.

Johnson, E.A. and Van Wagner, C.E. 1985. The theory and use of two fire history models. Canadian Journal of Forest Research 15: 214-220.

Johnson, E.A. and Wowchuk, D.R. 1993. Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. Candian Journal of Forest Research 23: 1213-1222.

Kapp, R.O. 1969. How to know pollen and spores. William C. Brown Co., Dubuque, Iowa.

Karl, T.R. and Riebsame, W.E. 1984. The identification of 10- to 20- year temperature and precipitation fluctuations in the contiguous United States. Journal of Climate and Applied Meteorology 23: 950-966.

Knox, J.L., Higuchi, K., Shabbar, A. and Sargent, N.E. 1988. Secular variation of northern hemisphere 50 kPa geopotential height. Journal of Climate 1: 500-511.

Krebs, C.J. 1989. Ecological methodology. Harper & Row, New York.

Larsen, C.P.S. and MacDonald, G.M. 1993. Lake morphometry, sediment mixing and the selection of sites for fine resolution palaeoecological studies. Quaternary Science Reviews 12: 781-792.

Lawless, J.F. 1982. Statistical models and methods for lifetime data. John Wiley & Sons, New York.

Lewis, H.T. 1977. Maskuta: the ecology of indian fires in northern Alberta. The Western Canadian Journal of Anthropology 7: 15-52.

Lewis, H.T. and Ferguson, T.A. 1988. Yards, corridors, and mosaics: how to burn a boreal forest. Human Ecology 16: 57-77.

Loehle, C. 1988. Tree life history strategies: the role of defenses. Canadian Journal of Forest Research 18: 209 - 222.

Luckman, B.H. and Innes, T.A. 1991. A bibliography and inventory of tree-ring studies in Canada. Current Research, Part E. Geological Survey of Canada, Paper 91-1E: 355 - 361.

MacDonald, G.M., Larsen, C.P.S., Szeicz, J.M. and Moser, K.A. 1991. The reconstruction of boreal forest fire history from lake sediments: a comparison of charcoal, pollen, sedimentological, and geochemical indices. Quaternary Science Reviews 10: 53-71.

MacLean, D.A. and Wein, R.W. 1977. Changes in understorey vegetation with increasing stand age in New Brunswick forests: species composition, cover, biomass, and nutrients. Canadian Journal of Botany 55: 2818-2831.

Maikawa, E. and Kershaw, K.A. 1976. Studies on lichen-dominated systems. XIX. The postfire recovery sequency of black spruce - lichen woodland in the Abitau Lake Region, N.W.T. Canadian Journal of Botany 54: 2679-2687.

Martell, D.L. 1983. Fire impact management in the boreal forest region of Canada. In Resources and dynamics of the boreal zone. Edited by R.W. Wein, R.R. Riewe and I.R. Methven. Association of Canadian Universiteis for Northern Studies. Ottawa. pp. 526-533.

Masters, A.M. 1990. Changes in forest fire frequency in Kootenay National Park, Canadian Rockies. Canadian Journal of Botany 68: 1763-1767.

McAndrews, J.H., Berti, A.A., and Norris, G. 1973. Key to the Quaternary pollen and spores of the Great Lakes Region. Life Science Miscellaneous Publications, Royal Ontario Museum, Toronto, Ontario, Canada.

McBride, J.R. 1983. Analysis of tree rings and fire scars to establish fire history. Tree-Ring Bulletin 43: 51-67.

McCune, B. and Allen, T.F.H. 1985. Will similar forests develop on similar sites Canadian Journal of Botany 63: 367 - 376.

Moody, G.H. and Cerezke, H.F. 1986. Forest insect and disease conditions in Alberta, Saskatchewan, Manitoba and the Northwest Territories in 1985 and predicitions for 1986. Canadian Forestry Service, Northern Forestry Centre Information Report NOR-X-276.

Morin, H., Laprise, D., and Bergeron, Y. 1993. Chronology of spruce budworm outbreaks near Lake Duparquet, Abitibi region, Quebec. Canadian Journal of Forest Research 23: 1497 - 1506.

Neave, H.R. and Worthington, P.L. 1988. Distribution free tests. Unwin Hyman Ltd., London.

Nelson, R.M. Jr. and Ward, D.E. 1980. Backfire particulate emissions and Byram's fire intensity. United States Department of Agriculture Forest Service Research Note SE-290.

Nienstaedt, H., and Zasada, J.C. 1990. White spruce. In Silivics of North America: 1, Conifers. Edited by Burns, R.M. and Honkala, B.H., Agricultural Handbook 654. United States Department of Agriculture and Forest Service. Washington. pp. 204 - 226.

Oechel, W.C., Hastings, S.J., Vourlitis, G., Jenkins, M., Riechers, G. and Grulke, N. 1993. Recent change of Arctic tundra ecosystems from a net carbon dioxide sink to a source. Nature 361: 520-523.