SUSTAINABLE FOREST MANAGEMENT NETWORK

RÉSEAU DE GESTION DURABLE DES FORÊTS

PROJECT REPORTS
2003/2004

Fire history in the Duck Mountain Provincial Forest, western Manitoba

Jacques Tardif

March 2004

Published: 31 March 2004

Related SFM Network Project:
tardifjfire6
Fire history reconstruction and response of the dominant tree species to climate in the Duck Mountain ecoregion, western Manitoba

A NETWORK OF CENTRES OF EXCELLENCE
UN RÉSEAU DE CENTRES D'EXCELLENCE

Project Report 2003/2004

Project Name: Fire history reconstruction and response of the dominant tree species to climate in the Duck Mountain ecoregion, western Manitoba.

Project Title: Fire history in the Duck Mountain Provincial Forest, western Manitoba.

Author: Jacques Tardif

Affiliation: Centre for Forest Interdisciplinary Research (C-FIR), University of Winnipeg, 515 Portage Avenue, Winnipeg, Manitoba, R3B 2E9. Email: j.tardif@uwinnipeg.ca

Date: March 2004

Executive summary

Public concerns about the impact of climate change and forestry practices on the Canadian boreal forests have increased in the last decades. The importance of understanding natural disturbances has been emphasized and new ideas integrating natural disturbance dynamics and forest management have emerged. However, large differences exist in the disturbance dynamics across the Canadian boreal forests and these preclude making large sweep generalisations about emulating natural disturbances in forest management. Little research has been conducted in Manitoba with regards to natural disturbances. In this study, we present a 300-year fire history reconstruction for the Duck Mountain Provincial Forest (DMPF) located in the boreal plains of western Manitoba. Standard dendrochronological methods were used and the time-since-fire distribution of forest stands within the DMPF was determined. Our results indicated that the fire cycle in the DMPF has dramatically changed since the early 1700. In the pre-settlement period (1700-1880), which corresponded to the late portion of the Little Ice Age, the fire cycle may have been around 55-years with, on average, up to 1.8% of the area burning each year. Throughout that period, we speculated that large, infrequent fires have occurred in conjunction with prolonged droughts. Such an extreme drought was observed from 1885 to 1895 and coincided with about 83% of the DMPF burning, i.e., an area equal to 283,580 ha. During settlement, numerous small fires were observed at the periphery of the DMPF and were speculated to origin from land clearing. Despite these frequent fires, the length of the fire cycle has increased to about 200 years. On average, about 0.5% of the landscape was burning every year. Since the last major fire to occur in 1961 the length of the fire cycle has been estimated to be over 15,000 years. The year 1961 coincided with the most severe drought in the 20th century for that region of Manitoba. At no other time in the 300-year record was there a period of 40-years or so with so little area burned. The impact of fire suppression needs to be further investigated but is speculated to play a major role in the lengthening of the fire cycle. The current time-since-fire distribution and age structure observed in the landscape are probably unprecedented. The imprint of the late 19th century fires coupled with settlement and fire suppression have been the dominant forces structuring the ecological processes of today. Our study questions the use of the current state of the DMPF has a benchmark on which to evaluate future anthropogenic impacts. It also emphasize the need to re-introduce larger scale disturbances in the DMPF and questions our ability to cope with potential risk associated with large, infrequent disturbances. The DMPF is unique with respect to i) its isolated nature along the Manitoba escarpment and ii) the existence of a provincial park within its boundaries. While silviculture practices can be adapted to replicate smaller scale disturbances, it may be required to also adapt them to alter the vulnerability to catastrophic fires. In regards to increase risks or uncertainties associated with global warming and fire suppression, managers should explicitly incorporate the risk of large, infrequent catastrophic fires in their long-term management plan. Given the specificity of the DMPF, this may mean establishing firebreaks or controlling fuel build-up. Other alternatives may also be examined. Our next steps will be i) to better quantify the fire cycle using statistical methods that take into account censored data, ii) to assess potential differences in fire cycle due to stand type, elevation, and distance to firebreak features and iii) to evaluate the role that forest harvesting have had in the rejuvenation of the forested landscape.

Keywords: Fire history, fire cycle, time-since-fire map, negative exponential model, drought, catastrophic fire

Introduction

Worldwide concerns about climate change and its potential impact on the boreal landscape are increasing (Kasischke and Stocks 2000). Predictions about warmer climate leading to shorter fire cycle and increasing forest disturbances have been made. Flannigan and Van Wagner (1991) predicted a possible 46% increase in the area burned across the Canadian boreal forest under a 2xCO_2 scenario. Large regional variations are, however, expected (Bergeron and Flannigan 1995; Weber and Flannigan 1997). Flannigan et al. (2001), using regional General Circulations Models' output, suggested that an increase in dry conditions may occur in both western and central Canada in response to climate warming whereas in the eastern Canadian boreal forest the increase in precipitation may overcome the effect of warming with respect to fire weather severity. However, empirical data from fire history showed that fire frequency and area burned have decreased since the end of the Little Ice Age (~1850) and this both in eastern and western Canada (Johnson et al. 1990; Bergeron and Archambault 1993; Johnson and Larsen 1991; Larsen 1997; Flannigan et al. 1998; Bergeron et al. 2001; Lesieur et al. 2002). Tree-ring based summer drought reconstructions extending back to 1605 AD suggest that changes in the fire regime in eastern and central Canada reflected a northward-displacement of the polar jet stream (Girardin et al. 2002; Girardin et al. in press). Evidence points toward a prominent warming of sea surface temperature along the North Pacific coast (Finney et al. 2000) as a potential cause for the shift in atmospheric circulation (Girardin et al. in press).

Public concerns about forest management practices have also been growing in the past decades (Burton et al. 2003). Policies and practices related to forest management are targeted and many oppose the ideas of clear-cutting, road building and temporary loss of habitats. In industrial landscape, the loss of mature old-growth forests also constitutes a major concern (Franklin 1993). Simultaneously, concepts like ecosystem management (Galindo-Leal and Bunnell 1995) and ecological certification (Lyke 1996; Heaner and Luckert 1998) for timber products are gaining momentum. Demands to integrate recreational and aesthetical values, soil and water resources as well as wildlife and biological diversity into forest management are growing (Perry 1998). As a consequence, the development of forestry practices that take forest ecosystem sustainability into account has become a priority.

A growing interest in the development of management practices that are based on understanding natural disturbance is observed. Natural disturbances in ecological systems are complex and include an array of characteristics such as spatial distribution, frequency, return interval, rotation period, predictability, severity and synergisms that all have to be considered (Pickett and White 1985; Attiwill 1994). In the boreal forests, fires are primarily responsible for the dynamics and maintenance of the habitat mosaic (Heinselman 1973; Rowe and Scotter 1973; Johnson 1992). Many studies showed that fire cycles vary within the Canadian boreal forest and estimates ranged from 50 years in western Canada to 500 years in the east (Foster 1983; Bergeron 1991; Larsen 1997; Johnson et al. 1998; Lesieur et al. 2002). Despite this crucial role, fire suppression has been one of the main goals of forest management in Canada (Ward and Mawdsley 2000). The impact of settlement and fire suppression on the forested landscape of Canada has also led to numerous discussions (Wright 1974; Baker 1992; Weir and Johnson 1998; Miyanishi and Johnson 2001;

Ward et al. 2001; Lefort et al. 2002). More recently, the development of forest harvesting techniques and the onset of large mechanized clearcuts have also dramatically changed the natural disturbance regime of the forest (Harvey and Bergeron 1989).

There is a growing consensus among researchers that, to be sustainable, forest management should be based upon a good understanding of forest dynamics and its natural disturbance regimes (Johnson et al. 1995; Bergeron and Harvey 1997; Gauthier et al. 2002; Johnson et al. 2003). Knowledge of the age-class distribution and the spatial arrangement of forest stands in a natural landscape constitute a key element in the implementation of sustainable forest management (Gauthier et al. 1996). New paradigms have emerged and emulating natural disturbances has been proposed as a way to better maintain biodiversity at the landscape level (Hunter 1993; Attiwill 1994; Gauthier et al. 1996; Bergeron and Harvey 1997; Harvey et al. 2003). This coarse-filter approach to biodiversity necessitates, however, that managers have a clear understanding of natural disturbances such as forest fires and insect outbreaks. Before silvicultural systems that are based on natural dynamics can be developed, natural disturbance regimes must first be defined and understood (Attiwill 1994). Our current understanding of fire dynamics and other disturbances across the Canadian boreal forest is fragmentary and precludes making abusive generalizations (Bergeron et al. 2001; Haeussler and Kneeshaw 2003). Clark (1990) emphasized the need for long-term disturbance history because short-term studies might be biased toward the period of cultural impact as well as toward the anomalous 20th century climate.

Today, the forests of central Canada have received little attention compared to other portions of the Canadian boreal forest. This region is, however, believed to form the transition between the eastern and the western Canadian boreal forest (Kurz and Apps 1999). Initial work in the Duck Mountain was conducted by Gill (1930) who was amongst the first Canadian scientist to use dendrochronology as a tool to reconstruct cyclical forest phenomena. The objective of this study was to fully reconstruct the fire history of the Duck Mountain Provincial Forest (DMPF). We wanted to characterize the regional specificity of the DMPF and to identify management opportunities that are in accordance with this specificity. This study constitutes an important step in the interpretation of vegetation development in the DMPF.

Methods

Study Area

The DMPF (51^0 39' 58"N and 100^0 54' 52" W), created in 1906 (Harrison 1934), forms part of the Manitoba Escarpment, which made up the western beach-edge of glacial Lake Agassiz, The escarpment is composed of a series of uplands identified from south to north as the Pembina Mountains, Riding Mountain, Duck Mountain, and the Porcupine Hills. More precisely, the DMPF lies about 58 km northwest of Dauphin. The study area covers about 3760 km^2 (Kenkel et al. 2004) and has a wide range of altitudes, with the eastern escarpment rising 300-400m in elevation and Baldy Mountain being the highest elevation point at 825 m above sea level (MPB 1973). A particularity of the DMPF is that it includes within its boundary the Duck Mountain Provincial Park (DMPP), which cover an area of 1424 km^2 and was established in 1961. Classified as a natural park, the DMPP has for objective to preserve ecosystems and maintain biodiversity as well as to accommodate a variety of recreational opportunities and resource uses (MC 2003). Although 61% of the DMPP land base is available for commercial logging, only a small percentage has been allocated each year (MC 2003).

The DMPF lies within the boreal plains ecoregion and is characterized by a humid micro thermal warm summer climate (Sauchyn and Hadwen 2001). Compared to the surrounding lowlands the plateau has cooler summers and winters and also receives about 50% more precipitation (MPB 1973). At higher elevation the length of the growing season is also reduced by late spring and early autumn frosts (Harrison 1934). The nearest meteorological station located at Swan River indicates mean annual temperature of 1.6^{0}C and total annual precipitation of 530.3 mm for the period 1971-2000 (Environment Canada 2003).

Due to its elevation, soil conditions and precipitation abundance, the DMPF is known for its variety of forest community types. Three distinct plant communities, the boreal forests, the deciduous forests and the upland meadows are found (MC 2003). The dominant tree species are trembling aspen (*Populus tremuloides* Michx.), white spruce (*Picea glauca* (Moench) Voss), balsam poplar (*Populus balsamifera* L.), black spruce *(Picea mariana* (Mill.) B. S. P.), paper birch (*Betula papyrifera* Marsh.), jack pine (*Pinus banksiana* Lamb), balsam fir (*Abies balsamea* (L.) Mill.) and tamarack (*Larix laricina* (DuRoi) K. Koch). The upland is mainly dominated by mixed forest and conifer stands (Sauchyn and Hadwen 2001). The trembling aspen forests dominate on the DMPF periphery and on lower portion of the upland region. Many small lakes and streams mark the landscape as well as many black spruce and tamarack dominated wetlands.

The history of the Duck Mountain (DM) is not fully documented (MC 2004). For most of its history, it constituted a barrier to settlement. For early explorers and traders, the DM was a source of furs and a barrier that has to be bypassed. Fort Dauphin, established in 1741 by La Vérendrye, forms one of many forts that were built in sight of the DM (MPB 1973). Selective logging of white spruce in the DM started in the late 1800s following the completion of the Canadian Northern Railway to Swan River in 1899. Homes and barns were built of local logs. At the turn of the century DM became an important source of timber with portable mills located in the DM and fixed mills in Grandview and Swan River (MC 2004). In the early 19th century, fires occurring in the DMPF were fought by local people to protect the stands being logged (Stilwell 1988). Some of the most notable fires occurred during the period 1885-1895, which burned almost half of the forested area of the uplands region (Gill 1930). In 1934, most of the timber license lied within the boundary of the DMPF (Harrison 1934). At that time, the DMPF was surrounded by settlement on all sides and its accessibility was considered unusually good (Harrison 1934).

Data Sampling and Laboratory Analyses

Our study started in the summer of 2000 and involved two intensive summers of field sampling and three years of data processing. The method used to reconstruct the fire history followed that outlined by Heinselman (1973) and Johnson and Gutsell (1994). Both air photos and forest inventory maps were reviewed to identify forest fire boundaries in the landscape. Compare to other areas in Manitoba, no proper survey or aerial coverage of the DMPF existed back in 1934 (Harrison 1934) and aerial photograph coverage of the DMPF dated back to 1946-1948. Once potential fire boundaries were identified, a systematic grid of UTM squares (10km by 10km) was overlaid over the DMPF (Fig. 1). Site (forest polygon) selection was constrained by accessibility and a total of 263 fire-sites were located, geo-referenced and sampled.

Time-since-fire dates were obtained for each fire-site by aging dominant trees/species known to regenerate well after fire. The post-fire colonization mechanisms of trembling aspen-balsam poplar-white birch (asexual reproduction within the burn) and, jack pine-black spruce (aerial seed banks within the burn) served to date stand origin (Greene and Johnson 1999). Priority was given to shade-intolerant species like jack pine and trembling aspen, which form even-aged cohorts following forest fires. Other species like white birch, tamarack, black spruce and white spruce were also used because of their greater longevity. At each site, 8-10 trees were sampled and two cores were extracted from opposite direction and close to the ground level using an increment borer. In young site (less than 80 years) only one core per tree was extracted. Four cores were systematically extracted from white birch, a species characterized by numerous missing rings. No attempt to determine the actual position of the root collar was done. Because our sampling mainly involved pioneer species like jack pine and trembling aspen, the dating errors described by DesRochers and Gagnon (1997) for shade-tolerant species were greatly reduced (Gutsell and Johnson 2002). To account for possible dating error due to mislocation of the root collar and/or for coring height, our data are presented in 10-year classes.

In addition to time-since-last-fire, indicators of previous fire were looked for. Each site was searched for fire-scarred trees, snags and down woody debris that were charred or not. Many cross-sections were collected. Snags are often the result of past fire and they can be used to extend back in time both the fire history and reference chronologies (Payette et al. 1989). Priority was given to jack pine snags, which may stand for over 100 years (Dansereau and Bergeron 1993). In many sites, it was thus possible to determine both time-since-last-fire and the time to the previous fire. To characterize each fire-site, ten modified Point Centre Quadrat (PCQ, Cottam and Curtis1956) separated by a pacing distance of 10m were sampled and at each point, the species and diameter of the closest tree in each quadrant was recorded. The data was used to calculate both relative frequency and dominance and to develop an importance value for each species. At each site, a soil pit was dig to classify soil according to texture, drainage, mottles and LFH depths (Zoladeski et al. 1995). This data will not be presented here.

In addition to the 263 fire-sites, 96 checkpoint-sites were sampled to assess the continuity of the time-since-fire across the landscape and/or to locate fire scarred trees and/or other indicators of past fire activity. These were done when a change in stand structure was observed. In these sites, usually three living trees and/or a few snags were sampled. At last, wood samples from 34 wetland sites were obtained from Locky et al. (2003). Logging in the DMPF has occurred since the late 19th century and we tried as much as possible to get the time-since-fire date prior to logging. In many areas, traces of logging could be used to determine the age of the forest prior to human disturbance. It is more than probable that we have not identified all early logging activities due to the small-scale practices of the time.

All cores and disks were prepared following standard procedures (Johnson and Gutsell 1994). All samples were dried and sanded using progressively finer grits of sandpaper. They were aged by tree-ring counts and visually crossdated using a binocular microscope. Skeleton plots were constructed for every tree species using a variation of the method proposed by Yamaguchi (1991). In the DMPF, both narrow rings and light rings proved to be the best pointer years. White rings (Hoggs 2002; Sutton and Tardif in press) in trembling aspen, balsam polar and white birch were systematically noted but were not totally reliable pointer years because of their speculated relation with the intensity of forest tent caterpillar (*Malacosoma disstria* Hubner) defoliation. Once cross-dated, the rings from the oldest tree from each site were measured to 0.01 mm using a VELMEX measuring system interfaced with a computer. A reference chronology was constructed for each species and made crossdating of dead wood easier. Crossdating was further validated using program COFECHA (Holmes 1983), which calculate cross-correlations to a lag of ten-years between each individual standardized measurement series and a reference chronology. Program COFECHA was also used to help dating dead material that could not readily be visually crossdated.

Time-Since-Fire Map and Fire Cycle

The time-since-fire date for each of the 359 site was either provided by the oldest trees in the overstorey cohort and/or by fire scar date. When samples did not allow determining time-since-fire with confidence the oldest tree was used and provided the minimum time-since-fire. This was mainly observed in old black spruce stands, and from old white spruce stands characterized by second to third generation trembling aspen. In our analysis, time-since-fire dates derived from pioneer species were considered non-censured and those derived from older stands dominated by shade-tolerant species like black spruce and white spruce were considered censored. For the total 359 sites sampled (Fig. 1), 472 fire intervals were generated with 18% considered censored. This information will be considered in later analyses using fire intervals and maximum likelihood survival analysis (Lesieur et al. 2002).

The fire cycle can be estimated using numerous methods (Johnson and Gutsell 1994; Lesieur et al. 2002). In this study, a time-since-fire map was constructed to provide an estimate of the most recent fire in each unit of the landscape. To create this map, our network of 359 sampling points was extended. First, we added the estimated stand initiation date obtained from 443 ground plots sampled during the most recent forest inventory of the DMPF. Second, we also added the estimated stand initiation date for 695 plots obtained from Louisiana Pacific Inc. A total of 1497 points was thus used to construct a time-since-fire map (Fig. 1). Our data was also complemented by the existence of fire records from 1914 and digital fire maps from 1976. Manitoba Conservation provided this fire history data.

Using the time-since-fire dates from these 1497 sampling points, Thiessen polygons were calculated using ArcView GIS 3.3 and no attempt to adjust polygon boundaries to those of the forest inventory was done. Preliminary analyses made it clear that we needed to construct two supplementary time-since-fire maps. The first one aimed at providing a view of the landscape in 1880 and was constructed using time-since-fire dates from 232 points where we had a fire date (90 from this project, 36 from forest inventory and 106 from LP). The second map aimed at providing a view of the landscape in 1900 and was constructed from a total of 1147 points (311 from this project, 319 ground plots and 517 sites from LP). All 1497 points were assumed to have originated from fire and when a site originated from harvesting the previous stand initiation age was used when possible.

The fire cycle can be defined as the number of years required to burn an area equal in size to the study area (Johnson and Gutsell 1994). To determine the fire cycle, either frequency or area data are needed. In this report, area data will be analyzed and the fire cycle will be determined using the negative exponential distribution model (Johnson and Van Wagner 1985). This model implies that the hazard of burning is constant with time and that the age of the forest does not influence its probability of burning. A negative exponential model was thus fit to the homogeneous time periods identified using the reverse cumulative time-since-fire distribution. In our study, censored data did not dominate the distribution and it was assumed that bias originating from the "missing tail" (Fox 1989; Finney 1995) was of minor importance. The parameter b in each of the regression model was estimated using the non-linear regression procedures found in SigmaPlot Version 8.02. As a comparison, we also calculated the fire cycle for the period 1914-2001 using fire history data provided by Manitoba Conservation. The natural fire rotation was calculated by dividing the number of year in the reference period by total area burned over the reference period divided by the study area size (Heinselman 1973). A truncated time-since-fire map (Johnson and Gutsell 1994) based on the 1914-2001 fire records will be presented and analyzed elsewhere.

Results

Stand Origins, Fire Scars and Radial Growth

The time-since-fire distribution derived from our 359 sites showed that a major recruitment peak occurred in both the 1880 and 1890 decades (Fig. 2). All tree species (stand types) showed this episode of major recruitment. As per 2002, the mean age of the DMPF has been estimated to be 108 ± 38 years (n=359) and compares to the estimation derived from the time-since-fire maps (Table 1). This average age provide an estimate of the general fire cycle of the study area for the entire time period covered including all stands and assuming a constant fire regime.

Looking at the individual species and/or stand type used to determine the time-since-fire distribution, trembling aspen had a mean age of 95 years (std=30, n=167), jack pine had a mean age of 103 year (std= 23, n=107), black spruce had a mean age of 148 years (std= 52, n=49), balsam poplar had a mean age of 127 years (std= 35, n= 13), white birch had a mean age of 124 years (std=53, n=9), eastern larch had a mean age of 135 year (std=42, n=8) and white spruce had a mean age of 153 year (std= 48, n=6). Trembling aspen stands were amongst the youngest sampled (Fig. 2). The oldest stands in the DMPF dated back to the early 1700s and were composed of living black spruce and tamarack tree growing on very moist sites. Some stands composed of old living white spruce and white birch trees were found dating back to the late 1700s. The distribution of jack pine snags also suggests that major fires may have occurred in the early 1700s, the mid 1700s and the early 1800s. Fire scarred trees were found in 19 sites and provided all together 20 different fire dates (Fig. 2e). Fire scars dated back to the early 1750s, the early 1800s, the 1840s, the late 1880s and numerous ones were observed between 1900 and 1950. The fire scar data support the results obtained from the time-since-fire date.

The tree-ring chronologies developed for the dominant tree species also indicated that the peak recruitment episode observed at the late 19th century coincided with a major fall in radial growth (Fig. 3). Fire scar years in the early 1750s, mid 1840s, 1875, late 1880s also appeared to coincide with period of reduced radial growth. Both jack pine and black spruce chronologies clearly showed prolonged growth depression in the 1750s, early 1800s, 1840s, the mid 1880s, 1930s and the early 1960s. Some of these periods are also visible in both the trembling aspen and the white spruce chronologies.

Time-Since-Fire Distribution

The time-since-fire map of the DMPF indicated that a large portion of the landscape originated between 1880 and 1899 (Fig. 4). The map derived for 1900 indicates that 83% of the DMPF area burned in that period, i.e., about 283,580 ha (Fig. 5). The time-since-fire map also showed that during the early 20th century, numerous small fires were observed at the (southwest) periphery of the DMPF (Fig. 4). The largest fire of the 20th century was that of 1961 with about 6% of the DMPF burning. The current vegetation mosaic of the DMPF (Fig. 4) also appears much different than that of the period prior to the catastrophic burns of the 1880s and 1890s (Fig. 6). Despite the lower accuracy of this time-since-fire map, large fires seem to have covered the DMPF in the past.

A quick look at the time-since-fire distribution and its reverse cumulative distribution indicate that our data does not follow a straight line (Fig. 7). A change in slope is characteristic of a mixed fire distribution. A clear break in the reverse cumulative distribution was observed and coincided with the catastrophic fires of the late 19th century. Despite the large area burned in that period, a lengthening of the fire cycle can be observed through time. The reverse cumulative distribution indicates that the proportion of the landscape in the younger age classes is relatively low today and that recent burns are rare (Fig. 7). This contrast with the pre-1880 period, which showed larger track of forests being burned in the landscape (Figs. 6 and 7 bottom). All things being equal, this change in slope suggests an alteration of the rate of burn since the early 1700s. Prior to the catastrophic burns of the late 1800s, the fire cycle during the period 1700-1880 was estimated to be 55 years (Fig. 7 bottom and Table 1). This meant that, on average, about 1.82% of the DMPA normally burned annually. During the 20th century, the fire cycle was estimated to be 455-years. This model provided a lower rsquare value and the data from the 20th century could be further divided into two distinct periods. During the early 20th century, the fire cycle was estimated to be about 200 years and it lengthened to more than 15,000 years in the second portion of the 20th century (Table 1). For the period 1961-2000, the negative exponential model was found to be not significant due to the near absence of burned area in the last 40 years. Calculating the natural fire rotation further corroborated this dramatic lengthening of the fire cycle (Table 2). Between 1914 and 2001, almost 300 fires were reported in the DMPF and about 23% of the landscape burned. Since the last major fire in 1961, little of the DMPF burned despite 86 fires being reported. A dramatic lengthening of the fire cycle was observed and at the current rate of burn (1962-2001), it would theoretically take more than 15,000 years for an area the size of the DMPF to burn.

Discussion:

Fire history and Fire Cycle

This study provides a unique perspective about fire dynamics in the boreal plains of Manitoba. The quality of the time-since-fire map is exceptional given the point coverage of the DMPF. The results presented are also unique because of the physiographical position of the Duck Mountain. As previously mentioned, the DMPF is part of the Manitoba Escarpment and constitute a 3,760-km2 island imbedded in an agricultural matrix. The uniqueness of the DMPF is further stressed by the presence of a provincial park within its boundary. This study will thus directly benefit our immediate partners: Louisiana Pacific Inc and Manitoba Conservation. Due to the different purposes-legislations pertaining to provincial forests and provincial parks, our findings will also interest a larger community involved in land and resource management. Our study will also increase public awareness about forest fire issues in sustainable forest management.

A unique feature of the DMPF fire history was the occurrence of catastrophic fires between 1885-1895. Johnson and Gutsell (1994) have suggested that the adequate study area size in fire history should be at least three times as large as the largest area burned in a single fire. The DMPF fire history breaks this rule with about 83% burning in a single decade. This contributed to the creation of a large deviation in the reverse cumulative area burned. The effect of these fires on the fire cycle estimation was, however, lowered by recalculating a time-since-fire map for the period prior to 1880. The effect of these large fires on the lengthening of the fire cycle observed in the early 20th century is, however, more difficult to quantify and a closer look at the distribution of fire intervals will be needed.

Our results suggested that the fire cycle in the DMPF was not constant during the time span covered by the study. According to Johnson and Gutsell (1994) mixed distribution may arise from pooling spatially distinct landscape with different fire frequencies and by temporal changes in fire frequency. Finney (1995) also argued that the presence of censored data might contribute to the rejection of the exponential negative model. Permanent features of the landscape such as elevation will need to be tested for their potential influence on our estimation of the fire cycle. The impact of other factors such as proximity to a water body, stand composition and censored data will also need to be addressed. Our findings suggested that black spruce forests growing in wetlands experience a longer fire cycle as indicated by their older mean age. Larsen (1997) reported similar findings in Alberta. Comments made by Harrison (1934) about the DMPF containing considerable areas of pure mature black spruce whereas most other stands of mixed spruce and poplar originated from the fires of the 1885 support our observation. The possibility that a longer fire cycle for black spruce results from an artefact due to its greater longevity compared to jack pine or trembling aspen will need, however, to be further investigated.

All things being equal, the fire history of the DMPF can be divided into three periods: pre-settlement, European settlement and modern fire suppression. Our results suggested that before settlement (1700-1880) and during the late portion of the Little Ice Age, a short fire cycle (50-60 years) punctuated by large fires characterized the DMPF. This fire cycle comparable to those reported in other portion of the Canadian boreal forest favoured the establishment of even-aged stands composed of short-lived pioneer species such as jack pine and trembling aspen. Old forest stands were probably rare and the proportion of open meadows and upland prairies could also have been more important than today. Despite the fact that we are unable to determine the origin of the pre-settlement fires (human or lightning), our tree-ring data suggested that these have occurred during period of extended drought. Prolonged droughts were observed from the 17th to the end of the 19th century (Girardin et al. 2002) and these periods were also reported in other regions of Manitoba (Tardif and Stevenson 2002) and western Canada (Sauchyn and Skinner 2001). Hope (1938) documented the drought of the 1840s. Harrison (1934) also mentioned that major fires had occurred in the DMPF 100-120 years prior to his study. Our finding that low radial growth in jack pine may be indicative of large fires is also supported by the finding of Larsen and MacDonald (1995) who reported a correlation between ring width variations and annual area burned in the Alberta's boreal forest.

The most dramatic period of catastrophic burns in our record occurred between 1885 and 1895. In the DMPF, fire scars were recorded in 1886, 1887 and 1889. Girardin et al. (2004) reported extreme drought indices during that period. According to Hope (1938), the drought of the late 1880s and early 1890s was apparently centred around south-central Alberta and coincided with many farms being abandoned on the Canadian plains. Tande (1979) observed that a large portion of Jasper National Park burned in 1889. Despite the absence of information on fire intensity, our result indicated that about 83% of the DMPF burned during this 10-year period. Harrison (1934) described a period "of fires of exceptional severity, which extended from 1885 to 1896". Gill (1930) wrote "In such years fires will likely burn through the winter and possibly start up again the following spring, as actually did happen in the 1885-95 period".

The fire history of the DMPF also appeared to be independent of that of nearby island-type components of the Manitoba escarpment distributed in a prairie sea. For instance, the major fires occurring in the DMPF were not reported by Gill (1930) who sampled in the Riding Mountain and Porcupine Forest Reserves. The Porcupine Forest Reserve (PFR) apparently share little fire dates with the DMPF. No catastrophic fires were reported in the 1885-1895 decade (Gill 1930, Harrison 1934). The entire east slope of the PFR was, however, practically cleaned by severe burns in 1919 (Harrison 1934). Severe burns were also observed in 1980. No major fires were reported in the DMPF in these years. These findings suggest that large catastrophic un-synchronized fires occur among the Manitoba escarpment highlands. Difference in lightning occurrences may be at the origin of these differences. This could be analogue to the independence of fire years among lake islands reported by Bergeron (1991). The impact of aboriginal people and their use of fire (Lewis and Ferguson 1988) do not seem to have been documented for the Manitoba Escarpment and this also merit further research. In addition, the fire records from the DMPF do not correspond well with that developed in Minnesota by Heinselman (1973). No major fires occurring in the 1885-1895 decade was reported by Heinselman (1973) and this suggests great spatial variability in weather conditions leading to forest fires. For instance, Heinselman (1973) reported that 1864 was an intense fire year and that both 1863 and 1864 were very dry years in Winnipeg, Manitoba. The year 1864 is not showing in the DMPF fire record and the tree-ring chronologies indicate average radial growth.

Since European settlement, a lengthening of the fire cycle was observed. Part of it may be due to climate. Our tree-ring chronologies provided indication that the 20th century may have been less prone to prolonged drought when compared to the previous centuries. Sauchyn and Skinner (2001) reported that the 20th century have had the least drought in the past 500 years. In addition to a climate less conductive to fire, part of the lengthening observed in the fire cycle could be due to the large track of young forests originating from the 1885-1895 fires. In the early settlement phase, numerous small fires occurred at the periphery of the DMPF. It is speculated that many of these fires were ignited during clearing of forest for agriculture. A similar increase in forest fires associated with forest clearing in early stages of settlement was reported in the mixed wood forest of Saskatchewan (Weir and Johnson 1998) and western Quebec (Lefort et al. 2002). Our results also concord with those of Lefort et al. (2002) who observed that since settlement, most of the burned area occurred in the early 20th century with a marked decreased in forest fires as fire suppression became more efficient. The reduced probability of fires originating outside the DMPF (agricultural and/or prairie fires) also constitute an element to consider when looking at the lengthening of the fire cycle in the late portion of the 20th century. The last large fire in the DMPF occurred during the extremely dry year of 1961 and burn about 6% of the study area. This fire, which may have been lightened by a camper, was detected in August 1961 and was controlled in early September (Kenkel et al. 2004). Since 1961, very few fires were allowed to burn and the post-1961 fire cycle was estimated to be above 15,000 years. This fire cycle, much longer than those reported for the forest-tundra (Payette et al.1989; Monson 2004), needs, however, to be interpreted with caution given the relatively short period (40 years) of data used in its calculation.

Implications for forest management

The dramatic lengthening of the fire cycle observed in the DMPF has had or will have numerous impacts on the landscape and on its diversity. Heinselman (1973) had suggested that both settlement and intentional fire suppression have altered the natural fire regime in Minnesota and this is presumably the case in the DMPF. Baker (1992) observed that settlement and fire suppression have had an impact on landscape diversity. Our data indicated that the current state of the DMPF may be unprecedented. Pollen analysis could probably help confirm this hypothesis. The finding of northern white-cedar pollen in the DMPF bogs would indicate that longer fire cycles have prevailed in the past. Northern white-cedar, a late-successionnal species in the eastern boreal forests (Bergeron and Dubuc 1988; Bergeron and Dansereau 1993) is currently absent from the DMPF. Disjunct populations, however, occur in north-central Manitoba, well outside the limit of the species continuous range of distribution. Preliminary investigations (Tardif and Stevenson 2002) suggested that long fire cycle might be allowing these disjunct populations to maintained themselves.

In the DMPF, the mean age of the forests is about 110 years and the current level of diversity may not constitute a benchmark by which we can assess the impact of forest management. As indicated by Heinselman (1973), major changes in the plant, animal and environmental complex are to be expected from the removal of fire. If we accept that the pre-settlement fire cycle was in the order of 50-60-years, young stands composed of pioneer species such as jack pine and trembling aspen have predominated in the past. At the opposite, a longer fire cycle would favour late successionnal (longer lived) species like black spruce, white spruce and balsam fir. A higher proportion of older age, uneven-aged stands would result. A lengthening of the fire cycle thus has important impacts on the composition of the forest mosaic and its age distribution (Bergeron and Dubuc 1989; Bergeron and Dansereau 1993). In the DMPF, the cohorts recruited after the 1885-1895 decades are entering a transitional phase. The dominance of shade-tolerant species should increase in the next decades as a consequence of increasing mortality of shorter-lived species. With time and in the absence of fire, the importance of jack pine and trembling aspen in the landscape will decrease. Field indications have revealed that some forest stands now composed of trembling aspen once had a component of jack pine as indicated by numerous jack pine snags. In these sites, a long fire interval has precluded jack pine to regenerate. In such stands, a shift in composition from jack pine to trembling aspen has occurred. In other stands, the dominance of black spruce may be increasing due to its shade tolerant characteristics. In absence of fire, secondary disturbances like insect outbreaks and windthrows dominate stand dynamics (Bergeron and Leduc 1988; Bergeron et al. 2001). Forest tent caterpillar outbreaks may play a role in speeding-up succession toward a larger importance of white spruce in the landscape. We are currently completing a reconstruction of the forest tent caterpillar outbreaks in the DMPF and looking at susceptibility of aspen stands in relation to age and stand composition.

From a forest management perspective, the impact of our findings will depend on the definition given to a socially acceptable forest rotation length and how it is translated into management practices that focus on the maintenance of stand composition and structures similar to those occurring under a natural environment (Gauthier et al. 1996). This choice will constitute an initial benchmark on which to base management objectives and the proportion of stands that should be allowed to develop above the rotation age. In Quebec, Bergeron et al. (2001) have suggested that the current average time-since-fire age derived from their 300-year fire history be used as a baseline in strategic planning of harvesting activities in their region. One of the reasons leading to the adoption of mean stand age criteria was its stronger inertia when compared to the fire cycle (Bergeron et al. subm.). The mean age of the forests in the DMPF is currently about 110 years. If forest management under a 110 year fire cycle is deemed socially acceptable for the DMPF, we could estimate the proportion of even-aged, irregular and uneven-aged stand types that would need to be recreated using different silvicultural treatments (Bergeron et al. 1999). Future work based on an applicability of the disturbance approach to forest management will start this fall with a thorough analysis of the most recent land base forest inventory of the DMPF.

Another implication of our findings to forest management concerns the near absence of forest fires in the DMPF and the increased risk of future catastrophic fires as forest fuels accumulate. Gill (1930) had categorized the fire hazard in the Duck Mountain as being of two types. Spasmodic fire hazards were reported to arise from short-term weather conditions conductive to forest fires and periodic fire hazards were reported to be the consequences of many years of drought. Gill (1930) advocated increasing, if not maximizing, fire detection and suppression efforts when two or three abnormally dry year occurs. The current level of fire suppression in the DMPF may increase the risk of large catastrophic fires. As mentioned earlier, increase fire hazards are predicted as a consequence of warming in central Canada. Given the adequate weather conditions and fuel load, the probability of large infrequent catastrophic fires like those of the late 19th century is not excluded. Large, infrequent disturbances (LIDs) such as the 1885-1895 fires may characterized the Manitoba escarpment as a whole including Riding Mountain National Park, Duck Mountain Provincial Forest and Porcupine Provincial Forest. These LIDs are ecologically important because of the imprint they leave on ecosystems (Turner and Dale 1998). When looking at the landscape of today, the fires of the late 19th century still constitute a dominant force structuring the DMPF. Ecological processes like succession are largely a function of these fires and may be much more complex that simple succession model would assume (Turner et al. 1998).

In terms of forest management, the potential for LID needs to be seriously considered. According to Dale et al. (1998), managers can deal with LID in four ways. They can modify i) the landscape prior to disturbance to decrease fire size and maybe fire frequency (e.g., fire breaks), ii) the disturbance itself (e.g., fire suppression), the post-disturbance (e.g., plantation) and the recovery process (e.g., successionnal processes). Our data suggests that large, infrequent fires have been part of the natural dynamics of the DMPF and in a context of multiple use (harvesting, hunting, recreation, conservation), it should be managed to alter the vulnerability to large spread fire. This could involve establishing fire breaks, forest fuel control, prescribed burning and making use of silviculture in a variety of ways to decrease fire hazard. Compared to small and frequent disturbances that can be more easily incorporate in planning and management (silvicultural design to replicate small disturbances), large disturbances are seldom incorporated in management plan (Dale et al. 1998).

This study thus questions our ability to properly manage forested landscape even in the absence of harvesting. In the DMPP, only disturbances like insect and disease are allowed and wildfire are suppressed (MC 2004). Manitoba Conservation, however, recognizes the importance of natural disturbance in maintaining natural areas and recognizes the need to develop strategies to enable or mimic natural disturbance under controlled conditions. These strategies may include controlled burning, harvesting and planting. In a landscape like the DMPF, it appears essential that some kind of disturbance be maintained to assure a certain level of biodiversity. In this study, harvesting was not considered and it will be interesting to address its impact on the rejuvenation of the landscape. In absence of fire, forest harvesting may be the only viable way to manage the DMPF in a context that better promote the ecological integrity of the forest and its long-term economical and social values.

Conclusion:

Our result showed that the current time-since-fire distribution in the DMPF is largely the result of large catastrophic fires that occurred at the end of the 19th century. Before these events, the fire cycle of the Duck Mountain was estimated to be 50-60 years. Since settlement, a dramatic increase in the length of the fire cycle was observed. This may have resulted from the imprint left by the catastrophic burns of the 1885-1895 decade, by a climate less conductive to severe drought, by smaller area burned resulting from agricultural development and fire suppression. The current ecological conditions of the DMPF may be unprecedented and in no other period in our reconstruction was there a period of 40 years with a near absence of fire. One of the main conclusion of this study concerns the need to re-introduce larger disturbances in the DMPF. The need to develop silvicultural practices to lower the risk of large infrequent fires is also emphasized given the risk associated with future climate change and the current level of fire suppression.

The DMPF holds a provincial park within its boundaries and policy harmonization will be needed among the different partners and land managers. Given the nature of the DMPF, a socially acceptable compromise will need to be reached when considering the ecological integrity, the social values and the economical viability of the region. In the DMPF, the historical role of fire has been to rejuvenate the forests and to create a dynamics mosaic of forest structure and composition at the landscape level. Today, in the near absence of fire, forest harvesting may be the only larger-scale disturbance occurring in the landscape. In the absence of fires, the DMPF forests will follow new successionnal pathways that could lead to unpredictable impacts on the flora and fauna. The majority of the forested stands in the DMPF are now in a transitional phase and it is believe that major changes will occur in the landscape as a consequence of fire suppression. The current characteristics of the landscape may also affect in unpredictable way the ability of the system to recovery from future catastrophic fires if such fires were to occur.

The next steps of our study will be to complete the analysis of the time-since-fire data by quantifying the fire cycle by stand types, elevation classes and by proximity to fire break features (lake, river, stream and bog). We also want to account for censored data. We will also take a closer look at the potential linkage between physiographic features and old-growth forests. More archival work will be conducted in relation to fire origins. We also wish to address the impact of harvesting in relation to its disturbance role by overlaying the harvested area to the burned area for the period where data is available. The three cohorts model develop in Quebec for the mixed wood boreal forest will also be looked at for its applicability to the DMPF. This will result in the analysis of the most recent land base inventory data. We will be establishing the proportion of stand types to be maintained in the DMPF following different fire cycles as well as the combination of silvicultural strategies (clearcut, partial cut and selective cut) that would be needed under such fire cycles. At last, the three cohorts model could also be made more realistic by allowing portion of the landscape to be harvested before attaining the theoretical rotation age. A more realistic model would also allow for compositional change to occur in mixed stands by varying cutting intervals.

Acknowledgement:
The Sustainable Forest Management Network (National Centres of Excellence) funded this research. Our industrial partner, Louisiana Pacific Limited, provided digital geographic data and logistical support in the field. Thanks to Margaret Donnelly, Paul Leblanc, Donna Grassia, and Steven Hills and others at Louisiana Pacific Canada (Swan River, MB). I also thank Manitoba Conservation for providing access to historical fire maps and digital geographic fire data and the Mixed Wood Forest Research and Advisory Committee for providing accommodation facilities at the Goldeneye Field Station. I thank France Conciatori who supervised the dendrochronological portion of the study from data collection to preparation of the time-since-fire maps. I thank all the students who participated in this project: Norm Aime, Erik Berglund, Cara Gill, Jennifer Joa, Derrick Ko Heinrichs, Alanna Sutton, Monika Thiessen and Christopher White. I also thank Martin Girardin and Dr. Sylvie Gauthier for their constructive comments on an earlier draft of this report.

References:

Attiwill, P.M. 1994. The disturbance of forest ecosystems: the ecological basis for conservative management. Forest Ecology and Management 63: 247-300.

Baker, W.L. 1992. Effects of settlement and fire suppression on landscape structure. Ecology 73: 1879-1887.

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". Holocene 3: 255-259.

Bergeron, Y. and Dansereau, P. 1993. Predicting the composition of Canadian southern boreal forest in different fire cycles. Journal of Vegetation Science 4: 827-832.

Bergeron, Y. and Dubuc, M. 1989. Succession in the southern part of the Canadian boreal forest. Vegetatio 79: 51-63.

Bergeron, Y. and Flannigan, M. 1995. Predicting the effects of climate change on fire frequency in the southeastern Canadian boreal forest. Water, Air and Soil Pollution 82: 437-444.

Bergeron, Y. and Harvey, B. 1997. Basing silviculture on natural ecosystem dynamics: an approach applied to the southern boreal mixedwood forest of Quebec. Forest Ecology and Management 92: 235-242.

Bergeron, Y. and Leduc, A. 1998. Relationships between change in fire frequency and mortality due to spruce budworm outbreak in the southeastern Canadian boreal forest. Journal of Vegetation Science 9: 493-500.

Bergeron, Y., Gauthier, M., Flannigan, M. and Kafka, V. subm. Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Quebec. Ecology 0:00-00.

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P. and Lessieur, D. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. Canadian Journal of Forest Research 31: 384-391.

Bergeron, Y., Richard, P.J.H., Carcailler, C., Gauthier, S., Flannigan, M. and Prairie, Y. 1999. Variability in fire frequency and forest composition in Canada'a southeastern boreal forest: a challenge for sustainable forest management. Conservation Ecology 12. Article 6. Available from http://www.consecol.org/vol2/iss2/art6 [cited February 2004].

Burton, P.J., Messier, C., Weetman, G.F., Prepas, E.E., Adamowicz, W.L. and Tittler, R. 2003. The current state of boreal forestry and the drive for change. Chapter 1. *In* Towards sustainable management of the boreal forest. *Edited by* Burton, P.J., Messier, C., Smith, D.W. and W.L. Adamowicz, NRC Research Press, Ottawa, Ontario, Canada. pp.1-40.

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

Cottam, G. and Curtis, J.T. 1956. Use of distance measures in phytosociological samplings. Ecology 37: 451-460.

Dale, V.A., Lugo, A.E., MacMahon, J.A. and Pickett, S.T.A. 1998. Ecosystem management in the context of large, infrequent disturbances. Ecosystems 1: 546-557.

Dansereau, P. and Bergeron, Y. 1993. Fire history in the southern boreal forest of northwestern Quebec.

Canadian Journal of Forest Research 23: 25-32.

Desrochers, A. and Gagnon, R. 1997. Is ring count at ground level a good estimation of black spruce age? Canadian Journal of Forest Research 27: 1263-1267.

Environment Canada. 2003. Canadian Monthly Climate Data and 1971-2000, Normals. Environment Canada. Ottawa.

Finney, M.A. 1995. The missing tail and other considerations for the use of fire history models. International Journal of Wildland Fire 5:197-202.

Finney, B., Gregory-Eaves, I., Sweetman, J., Douglas, M., and Smol, J.P. 2000. Impacts of climatic change and fishing on Pacific salmon abundance over the past 300 years. Science 290: 795-799.

Flannigan, M. and Van Wagner, C. 1991. Climate change and wildfire in Canada, Canadian Journal of Forest Research 21, 61-72.

Flannigan, M.D., Bergeron, Y., Engelmark, O. and Wotton, B.M. 1998. Future wildfire in circumboreal forests in relation to global warming. Journal of Vegetation Science 9: 469-476. 2001.

Flannigan, M., Campbell, I., Wotton, M. Carcaillet, C., Richard, P. and Bergeron, Y. 2001. Future fire in Canada's boreal forest: paleoecology results and general circulation model – regional climate model simulations. Canadian Journal of Forest research 31: 854-864.

Franklin, J.F. 1993. Preserving biodiversity: species, ecosystems, or landscapes? Ecological Application 3: 202-205.

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

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

Gauthier, S., Leduc, A. and Bergeron, Y. 1996. Forest dynamics modelling under natural fire cycles: a tool to define natural mosaic diversity for forest management. Environmental Monitoring and Assessment 39: 417-434.

Gauthier, S., Lefort, P., Bergeron, Y. and Drapeau, P. 2002. Time since fire map, age-class distribution and forest dynamics in the Lake Abitibi Model Forest. Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, Sainte-Foy, Que. Inf. Rep. LAU-X-125E.

Gill, C.B. 1930. Cyclic forest phenomena. Forestry Chronicle 6: 42-56.

Girardin, M.P., Tardif, J., Flannigan, M.D., and Bergeron, Y. 2002. Reconstructing atmospheric circulation history using tree rings: one more step toward understanding temporal changes in forest dynamics. In Proceedings for the 3rd International Sustainable Forest Management Network Conference - Advance in forest management: from knowledge to practice, 13-15 November, Edmonton, Alberta. Edited by T.S. Veeman, P.N. Duinker, B.J. Macnab, A,G. Coyne, K.M. Veeman, and D. Korber. Edmonton, Alberta. pp. 105-110.

Girardin, M.P., Tardif, J., Flannigan, M.D., and Bergeron, Y. in press. Multicentury reconstruction of the Canadian Drought Code from eastern Canada and its relationships with paleoclimatic indexes of atmospheric circulation. Climate Dynamics 00:00-00.

Girardin, M.P., Tardif, J. Flannigan, M.D., Wotton, B.M. and Bergeron, Y. 2004. Trends and periodicities in the Canadian Drought Code and their relationships with atmospheric circulation for the southern Canadian boreal forest. Canadian Journal of Forest Research 34: 103-119.

Galindo-Leal, C. and Bunnell, F.L. 1995. Ecosystem management: implications and opportunities of a new paradigm Forestry Chronicle 71: 601-606.

Greene, D.F. and Johnson, E.A. 1999. Modelling recruitment of *Populus tremuloides, Pinus banksiana, and Picea mariana* following fire in the mixedwood boreal forest. Canadian Journal Forest. Research 29: 462-473.

Gutsell, S.L. and Johnson, E.A. 2002. Accurately ageing trees and examining their height-growth rates: implications for interpreting forest dynamics. Journal of Ecology 90: 153-166.

Haeussler, S. and Kneeshaw, D. 2003. Comparing forest management to natural processes. Chapter 9. *In* Towards sustainable management of the boreal forest. *Edited by* Burton, P.J., Messier, C., Smith, D.W. and W.L. Adamowicz, NRC Research Press, Ottawa, Ontario, Canada. P.p.307-368.

Harrison, J.D.B. 1934. The forests of Manitoba. Forest Service Bulletin 85, Department of the Interior, Ottawa, Canada.

Harvey, B.D. and Bergeron, Y. 1989. Site patterns of natural regeneration following clear-cutting in northwestern Quebec. Canadian Journal of Forest Research 19:1458-1469.

Harvey, B.D., Nguyen-Xuan, T., Bergeron, Y., Gauthier, S. and Leduc, A. 2003. Forest management planning based on natural disturbance and forest dynamics. Chapter 11. *In* Towards sustainable management of the boreal forest. *Edited by* Burton, P.J., Messier, C., Smith, D.W. and W.L. Adamowicz, NRC Research Press, Ottawa, Ontario, Canada. P.p.395-432.

Heaner, M.K. and Luckert, M.K. 1998. Forest certification economic issues and welfare implications. Canadian Public Policy 24: S83-S94.

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

Hogg, E.A., Hart, M. and Lieffers, V.J. 2002. White tree rings formed in trembling aspen saplings following experimental defoliation. Canadian Journal of Forest Research 32: 1929-1934. 2002

Holmes, R.L. 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin 43: 69-78.

Hope, E.C. 1938. Weather and crop history in western Canada. C.S.T.A. Review No 16: 347-358.

Hunter, M.L. 1993. Natural fire regimes as spatial models for managing boreal forests. Biological Conservation 65: 115-120.

Johnson, E.A. 1992. Fire and vegetation dynamics Studies from the North American boreal forest Cambridge University Press.

Johnson, E.A. and Gutsell, S.L. 1994. Fire frequency models, methods, and interpretations. Advances in

Ecological Research 25: 239-287.

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., 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., Miyanishi, K. and Weir, J.M.H. 1995. Old-growth, disturbance, and ecosystem management. Canadian Journal of Botany 73: 918-926.

Johnson, E.A., Miyanishi, K. and Weir, J.M.H. 1998. Wildfires in western Canadian boreal forest: landscape patterns and ecosystem management. Journal of Vegetation. Science 9: 603-610.

Johnson, E.A., Morin, H., Miyanishi, K., Gagnon, R. and Greene, D.F. 2003. A process approach to understanding disturbance and forest dynamics for sustainable forestry. Chapter 8. *In* Towards sustainable management of the boreal forest. *Edited by* Burton, P.J., Messier, C., Smith, D.W. and W.L. Adamowicz, NRC Research Press, Ottawa, Ontario, Canada. pp. 261-306.

Kasischke, E.S. and Stocks, B.J. 2000. Fire, climate change, and carbon cycling in the boreal forest. Ecological Studies 138. Springer-Verlag, New York

Kenkel, N. Foster, C., Caners, R. Lastra, R. and Walker, D. 2003. Spatial and temporal patterns of white spruce recruitment in two boreal mixedwood stands, Duck Mountains, Manitoba. Mountains, Manitoba. Final Project Report 2003-4, Sustainable Forest Management Network. University of Alberta, Edmonton, Alberta.

Kurz, W.A., and Apps, M.J. 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. Ecological Application 9: 526-547.

Larsen, C.P.S. 1997. Spatial and temporal variation in boreal forest fire in northern Alberta. Journal of Biogeography 24: 663-673.

Larsen, C.P.S., MacDonald, G.M. 1995. Relations between tree-ring widths, climate, and annual area burned in the boreal forest of Alberta Canadian Journal of Forest Research 25:1746-1755.

Lyke, J. 1996. Forest product certification revisited an update Journal of Forestry 94: 16-20.

Lefort, P., Gauthier, S. and Bergeron, Y. 2002. The influence of fire weather and land use on the fire activity of the Lake Abitibi area, eastern Canada. Forest Science. 49: 509-521.

Lesieur, D., Gauthier, S. and Bergeron, Y. 2002. Fire frequency and vegetation dynamics for the south-central boreal forest of Quebec, Canada. Canadian Journal of Forest Research 32: 1996-2009.

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

Locky, D.A., Bayley, S.E., and D.H. Vitt. 2003. The vegetational ecology of peatlands at Duck Mountain, Manitoba. An abstract published in the Proceedings of the Society of Wetland Scientists Conference, New Orleans, Louisiana, USA. June 8-13th, 2003.

Manitoba Parks Branch. 1973. Outdoor recreation master plan: Duck Mountain Provincial Park. Manitoba Department of Tourism, Recreation and Cultural Affairs, Parks Branch. Winnipeg.

Manitoba Conservation, 2003. Duck Mountain Provincial Park, Draft Management Plan, Draft Management Plan [Online], Parks and Natural Areas Branch, Winnipeg, Manitoba. Cited February 2004. Available at http://www.manitobaparks.com

Manitoba Conservation, 2004. Duck Mountain Provincial Park, Park Information and Maps [Online], Parks and Natural Areas Branch, Winnipeg, Manitoba. Cited February 2004. Available at http://www.gov.mb.ca/conservation/parks/popular_parks/duck_mtn/info.html

Miyanishi, K. and Johnson E.A. 2001. Comment- A re-examination of the effects of fire suppression in the boreal forest. Canadian Journal of Forest Research 31: 1462-1466.

Monson, K.M.M. 2004. Fire history and secondary vegetation succession in the forest-tundra near Churchill, Manitoba. M.Sc. thesis. Department of Botany, University of Manitoba.

Payette, S., Morneau, C., Sirois, L., and Desponts, M. 1989. Recent fire history of the northern Quebec (Canada) biomes. Ecology 70: 656 673.

Perry, D.A. 1998. The scientific basis of forestry Annual Review of Ecology and Systematic 29: 435-466.

Picket, S.T.A. and White, P.S. 1985???. The ecology of natural disturbance and patch dynamics Academic Press. New York.

Rowe, J.S. and Scotter, G.W. 1973. Fire in the boreal forest. Quaternary Research 3: 444-464.

Sauchyn, D.J., and Hadwen, T. 2001. Forest ecosystems and the physical environment, Duck Mountains, west central Manitoba. Final Project Report 2001 29, Sustainable Forest Management Network. University of Alberta, Edmonton, Alberta.

Sauchyn, D.J. and Skinner, W. R. 2001. A proxy PDSI record for the southwestern Canadian plains. Canadian Water Resources Journal 26: 253-72.

Stilwell, W.J. 1988. The Baldy Mountain cabin: the history and role of forest rangers and game wardens in the Baldy Mountain area. Regional Services Branch, Manitoba Department of Natural Resources, Winnipeg, Manitoba

Sutton, A. and Tardif, J. in press. Distribution and anatomical characteristics of white rings in *Populus tremuloides* Michx. IAWA Journal 00: 00-00.

Tande, G.F. 1979. Fire history and vegetation pattern of coniferous forest in Jasper National Park, Alberta. Canadian Journal of Botany 57: 49-60.

Tardif, J. and Stevenson, D. 2002. Radial growth - climate association of *Thuja occidentalis* L. at the northwestern limit of its distribution, Manitoba, Canada. Dendrochronologia 19: 1-9.

Turner, M.G. and Dale, V.H. 1998. Comparing large, infrequent disturbances: what have we learned. Ecosystems 1: 493-496.

Turner, M.G., Baker, W.L., Peterson, C.J. and Peet, R.K. 1998. Factors influencing succession: lessons from large, infrequent natural disturbances. Ecosystems 1: 511-523.

Ward, P.C. and Mawdsley, W. 2000. Fire management in the boreal forest of Canada. Pp. 66-84, In Kasischke, E.S. and Stocks, B.J. Fire, climate change, and carbon cycling in the boreal forest. Ecological Studies 138. Springer-Verlag, New York

Ward, P.C.; Tithecott, A.G. and Wotton, B.M. 2001. Reply- A re-examination of the effects of fire suppression in the boreal forest. Canadian Journal of Forest Research 31: 1467-1480.

Weber, M.G., and Flannigan, M.D. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: impacts on fire regimes. Environ. Rev. 5: 145-166.

Weir, J.M.H. and Johnson, E.A. 1998. Effects of escaped settlement fires and logging on forest composition in the mixedwood boreal forest. Canadian Journal of Forest Research 28: 459-467.

Wright, Jr. H.E. 1974. Landscape development, forest fires, and wilderness management. Science 186: 487-495.

Yamaguchi, D.K. 1991. A simple method for cross-dating increment cores from living trees. Canadian Journal of Forest Research 21: 414-416.

Zoladeski, C.A., Wickware, G.M., Delorme, R.J., Sims, R.A. and Corns, I.G.W. 1995. Forest Ecosystem classification for Manitoba. Special Report 2, UBC Press, British Columbia.

Table 1: Comparison of the fire cycle estimation using different data set. The mean age of the DMPF provide an overall estimate of the fire cycle. The parentheses indicate the average annual percent of the landscape burned under the different fire-cycles. All negative exponential models were non-significant for the period 1960-2002 indicating extremely long fire cycle due to the near absence of fires in the landscape. The referenced area used for the Duck Mountain Provincial Park was 339,761 hectares. N.A.: Not available, N.S.: Non-significant negative exponential model.

	Area burned as per 1880	Area burned as per 2002 (only point data)	Area burned as per 2002 (including recent fire maps)
Mean age (± std)	56 (±2)	111 (±10)	108 (±10)
Before 1880	55-yr (1.82%)	35-yr (2.86%)	36-yr (2.78%)
1900-2002	N.A.	625-yr (0.16%)	455-yr (0.22%)
1900-1960	N.A.	278-yr (0.36%)	200-yr (0.50%)
1960-2002	N.A.	N.S.	N.S.

Table 2: Natural fire rotation for the current past calculated from the fire area maps obtained from Manitoba Conservation. The fire data covers the period 1914 to 2001. The time periods were chosen to emphasize major changes in the fire cycle. The parentheses indicate the average annual percent of the landscape burned under the different fire-cycles. The referenced area used for the Duck Mountain Provincial Park was 339,761 hectares. Note that the 1961-fire burned about 21,297 hectares (6.3% of the territory) and constitutes the largest fire in the record.

Time period	Number of years	Reported ignition	Area burned (ha)	Natural fire rotation (years)
1914-2001	87	282	60786	486-yr (0.21%)
1914-1961	47	196	60089	266-yr (0.38%)
1962-2001	40	86	697	19,501-yr (0.0051%)

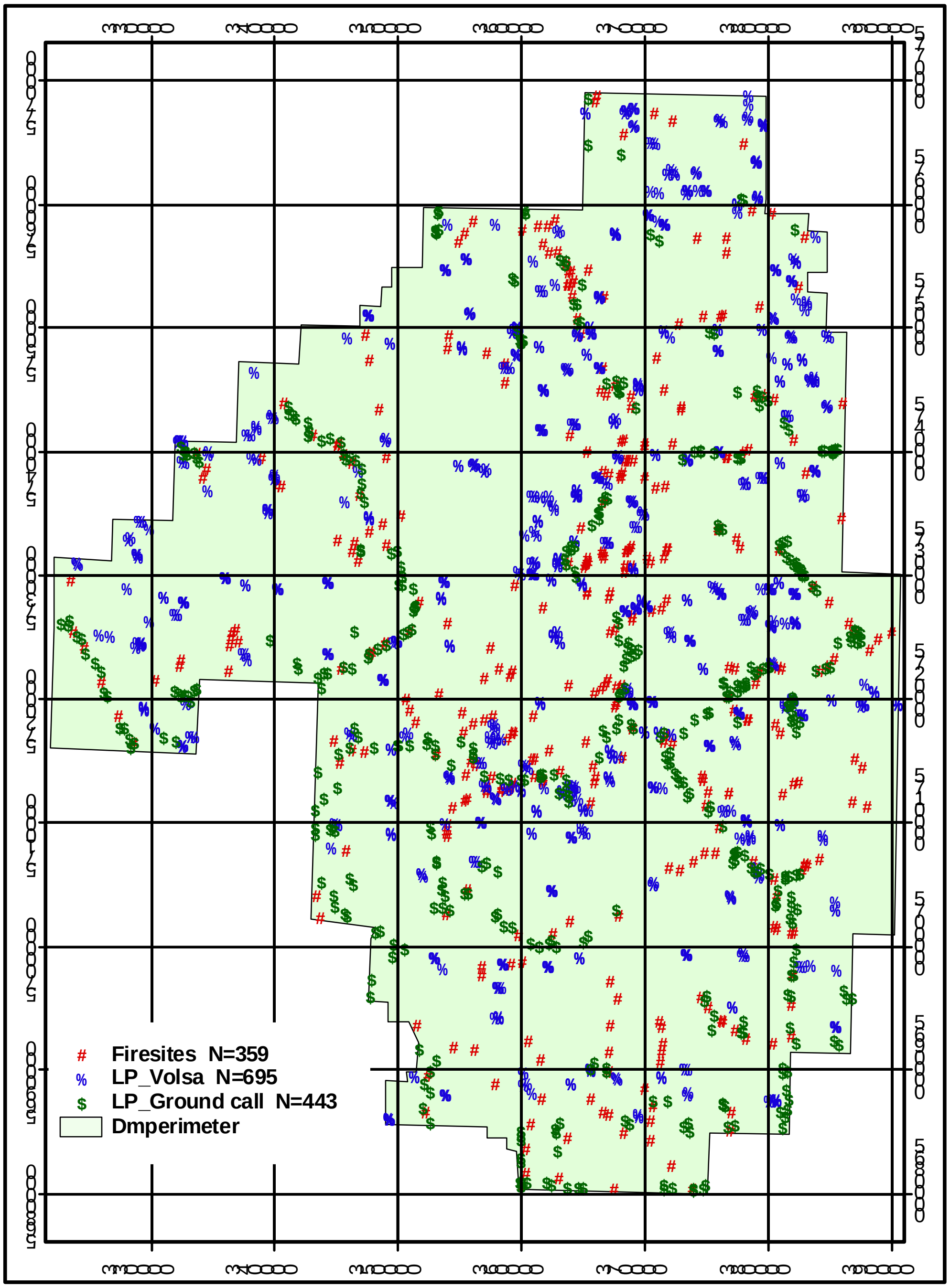

Figure 1: Map of the Duck Mountain Provincial Forest showing the location of the 1497 points used to determine the current time-since-fire map.

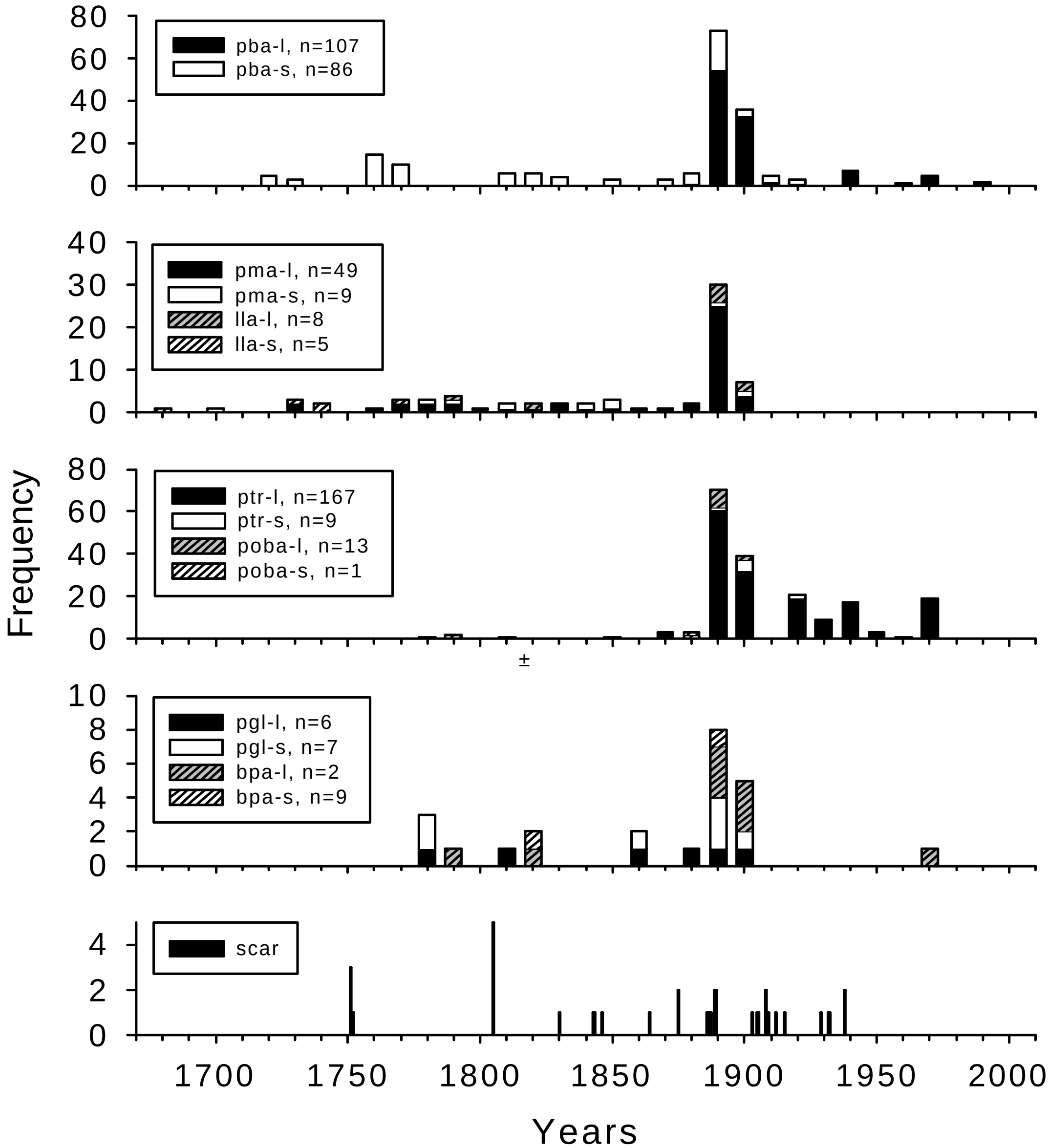

Figure 2: Time-since-fire distribution by species and/or stand types. Pba: *Pinus banksiana*, Pma: *Picea mariana*, Lla: *Larix laricina*, Ptr: *Populus tremuloides*, Poba: *Populus balsamifera*, Pgl: *Picea glauca* and Bpa: *Betula papyrifera*. The letter following the species indicates that stand origin was determined using either living trees (l, n=359 sites/dates) or snags (s, n=121 dates). Fire scar frequency is also indicated.

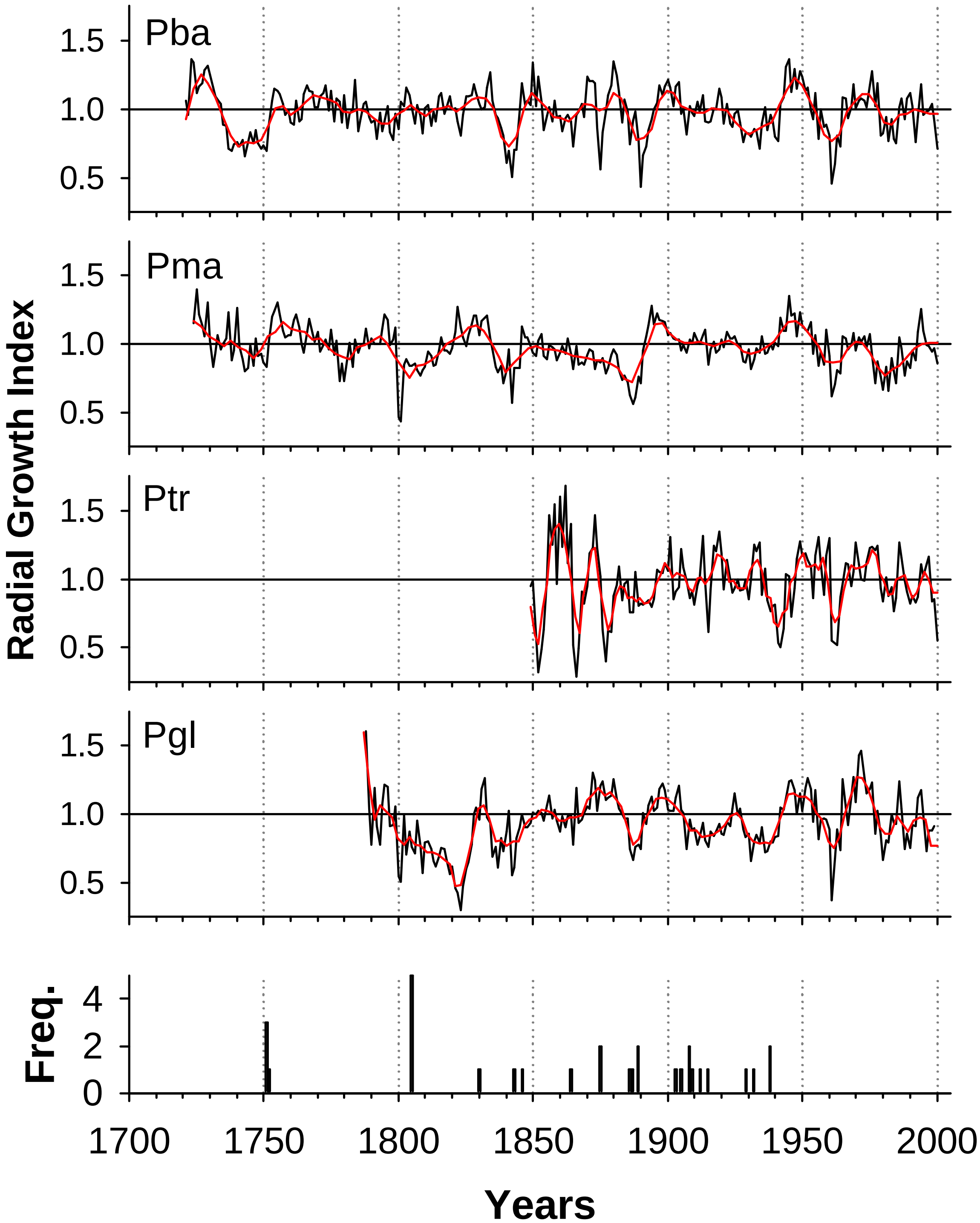

Figure 3: Tree-ring standard chronologies for four of the dominant tree species from the Duck Mountain Provincial Forest and frequency of fire scar dates. Pba= *Pinus banksiana*, Pma= *Picea mariana*, Ptr= *Populus tremuloides* and Pgl= Picea glauca. All chronologies start at a sample depth of five trees. The bold line refers to a running average.

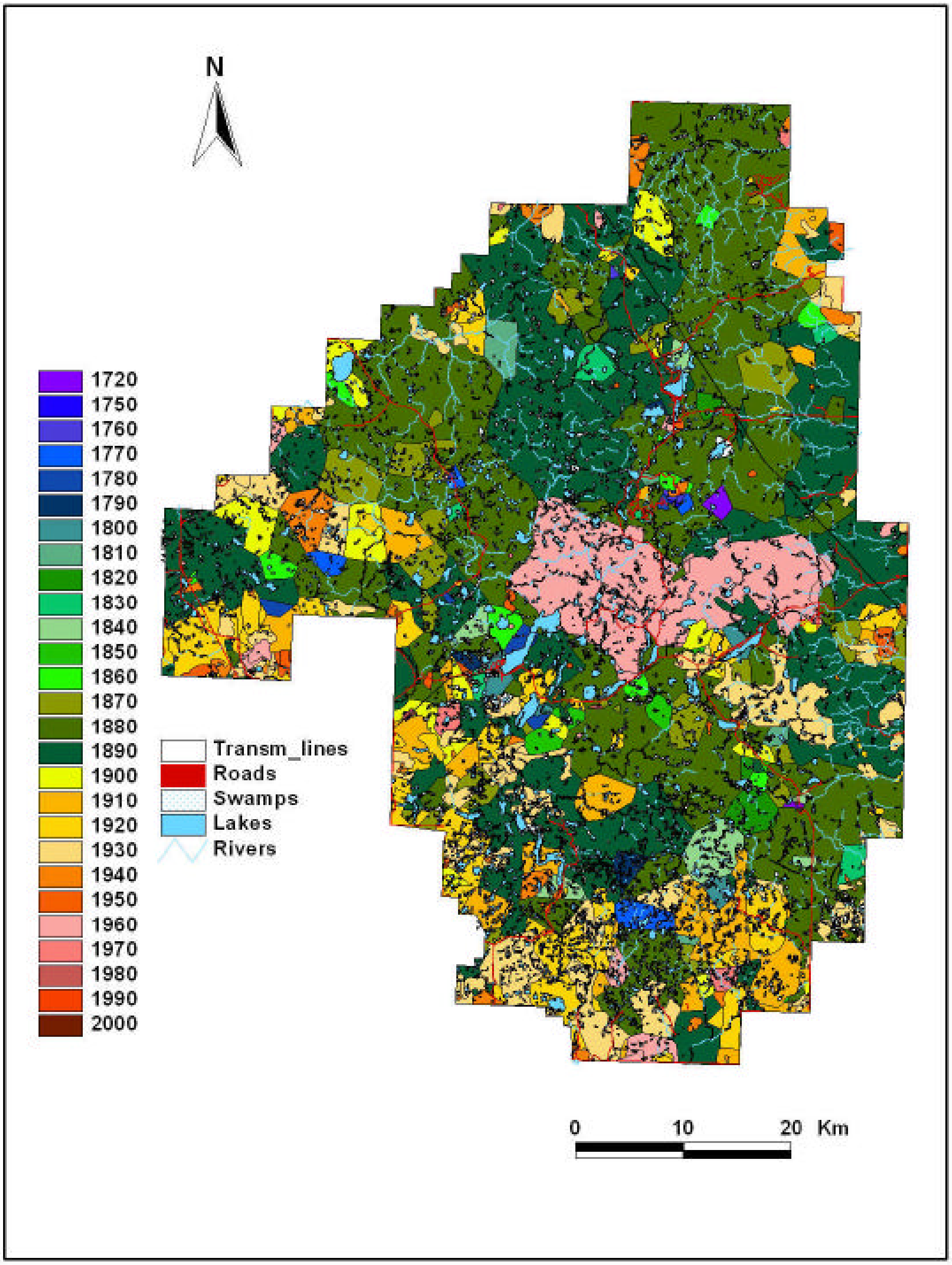

Figure 4: Time-since-last-fire map for the Duck Mountain Provincial Forest as of 2002 and including data obtained from Manitoba Conservation's archives (see methods). One can observed the numerous small fires occurring at the perimeter of the DMPF in the early 20th century and the area burned in 1961 in brown at the centre of the map.

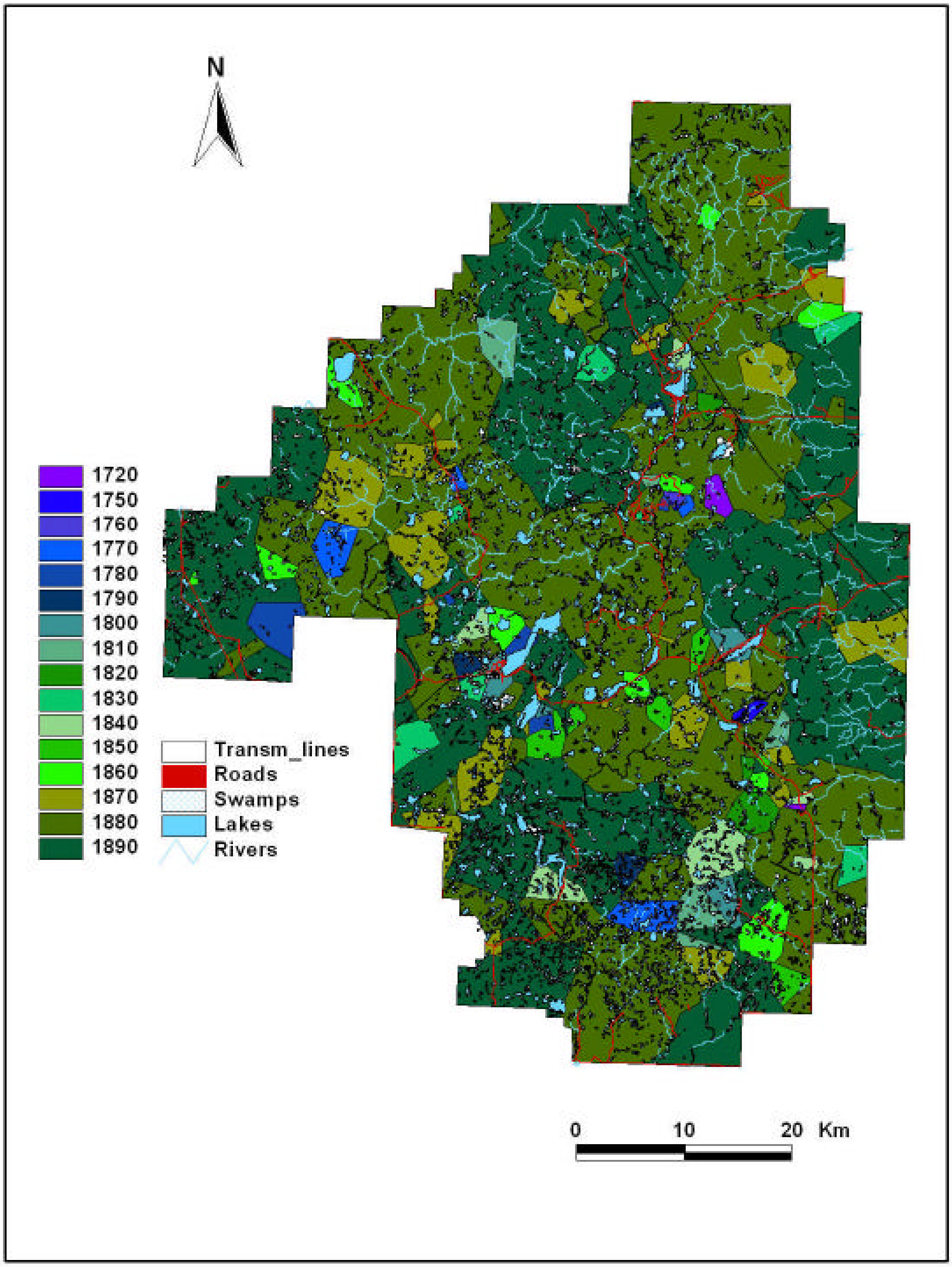

Figure 5: Time-since–last-fire map for the Duck Mountain Provincial Forest as if one was standing in the early 1900, immediately after the catastrophic burns of the 1885-1895 decade. The area burned in both 1880 and 1890 classes totalized 83% of the DPPF.

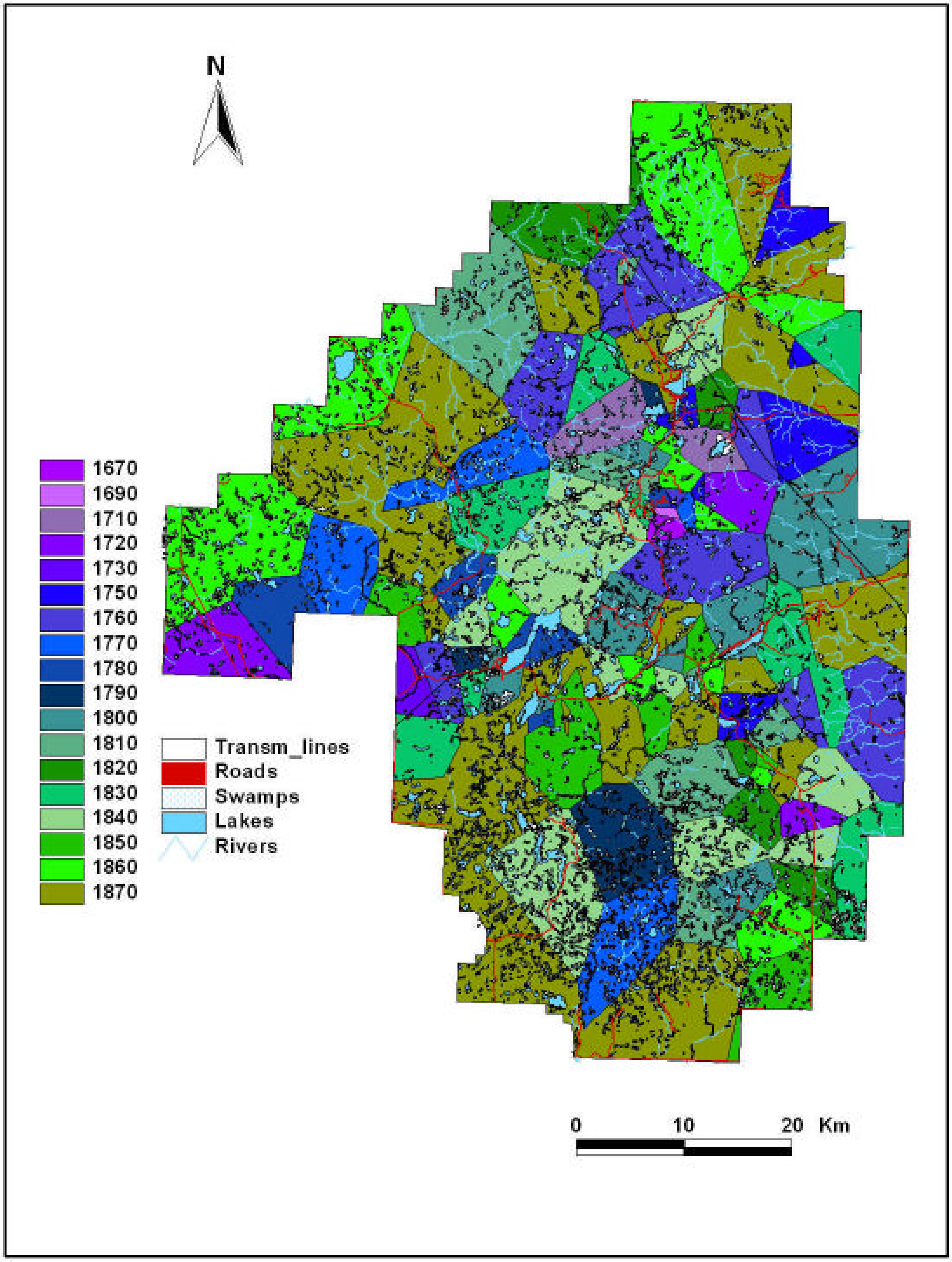

Figure 6: Time-since-last-fire map for the Duck Mountain Provincial Forest as if one was standing in the early 1880, i.e. before the catastrophic burn of the 1885-1895 decade. Large-scale fires may have occurred throughout the period covered as indicated by the colour scale.

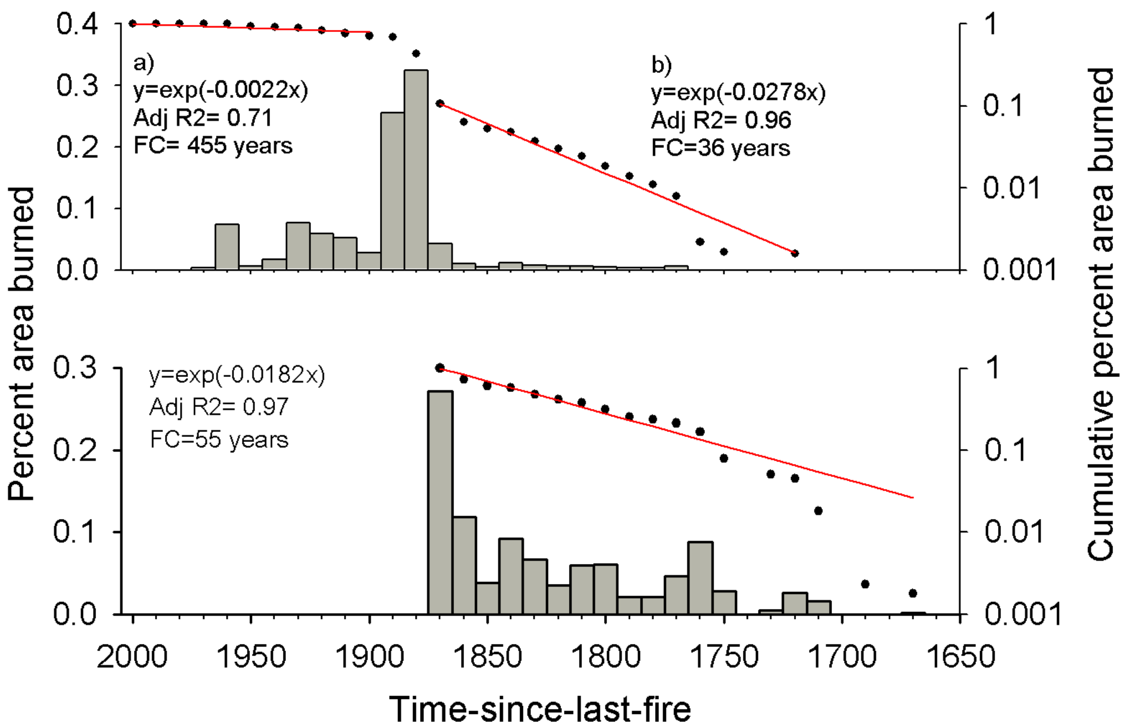

Figure 7: Time-since-last-fire distribution for the Duck Mountain Provincial Forest calculated from the data presented in Figure 3 and 5. The top figure represents the percent area burned as per 2002 and the bottom figure represents the percent area burned as per 1880. The equation for the negative exponential function, the adjusted-rsquare and the estimated fire cycle (FC) are indicated.