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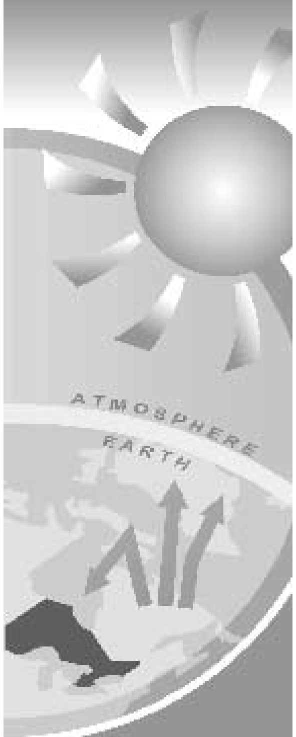
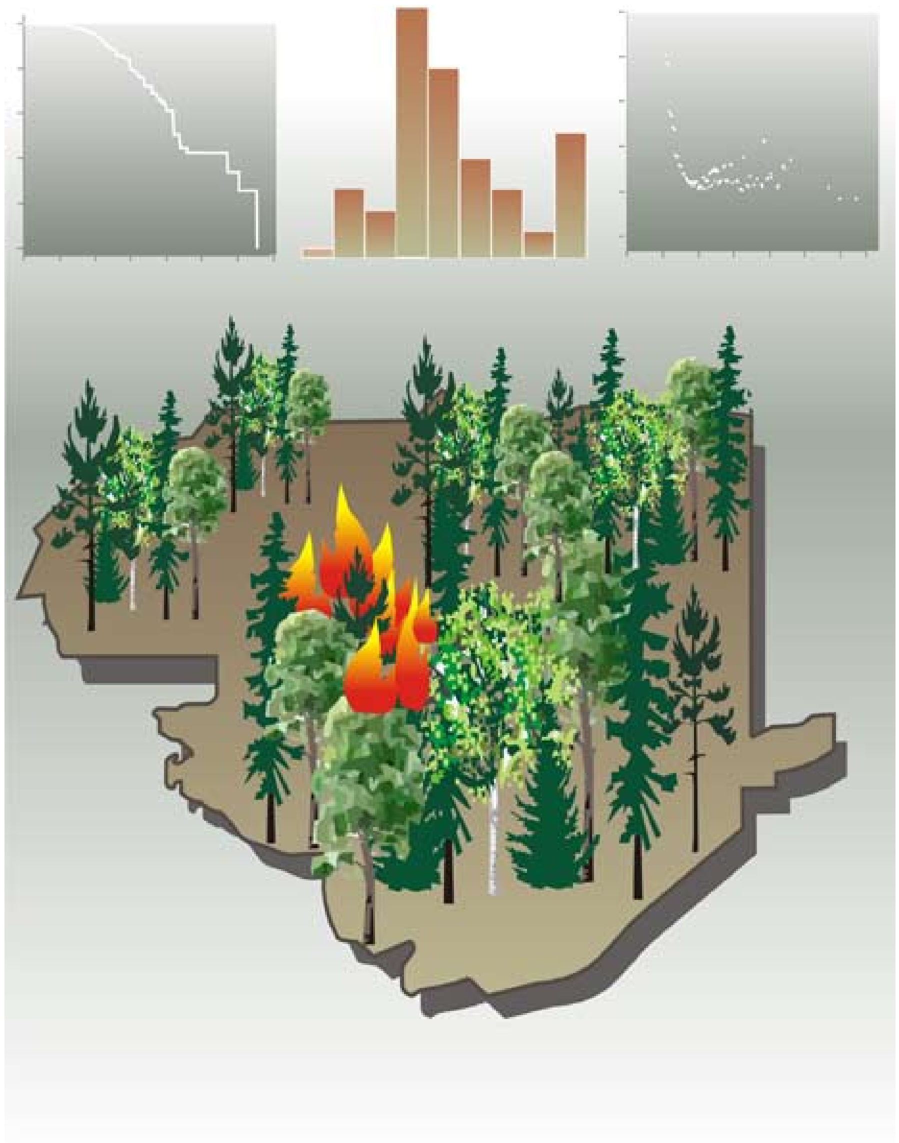
CLIMATE CHANGE RESEARCH REPORT

CCRR-18

Comparing Various Approaches for Estimating Fire Frequency: The Case of Quetico Provincial Park





Responding to Climate Change Through Partnership

Ministry of Natural Resources

Ontario

Sustainability in a Changing Climate: An Overview of MNR's Climate Change Strategy (2011-2014)

Climate change will affect all MNR programs and the natural resources for which it has responsibility. This strategy confirms MNR's commitment to the Ontario government's climate change initiatives such as the Go Green Action Plan on Climate Change and outlines research and management program priorities for the 2011-2014 period.

Theme 1: Understand Climate Change

MNR will gather, manage, and share information and knowledge about how ecosystem composition, structure and function – and the people who live and work in them – will be affected by a changing climate. Strategies:

- Communicate internally and externally to build awareness of the known and potential impacts of climate change and mitigation and adaptation options available to Ontarians.
- Monitor and assess ecosystem and resource conditions to manage for climate change in collaboration with other agencies and organizations.
- Undertake and support research designed to improve understanding of climate change, including improved temperature and precipitation projections, ecosystem vulnerability assessments, and improved models of the carbon budget and ecosystem processes in the managed forest, the settled landscapes of southern Ontario, and the forests and wetlands of the Far North.
- Transfer science and understanding to decision-makers to enhance comprehensive planning and management in a rapidly changing climate.

Theme 2: Mitigate Climate Change

MNR will reduce greenhouse gas emissions in support of Ontario's greenhouse gas emission reduction goals. Strategies:

- Continue to reduce emissions from MNR operations though vehicle fleet renewal, converting to other high fuel efficiency/low-emissions equipment, demonstrating leadership in energy-efficient facility development, promoting green building materials and fostering a green organizational culture.
- Facilitate the development of renewable energy by collaborating with other Ministries to promote the value of Ontario's resources as potential green energy sources, making Crown land available for renewable energy development, and working with proponents to ensure that renewable energy developments are consistent with approval requirements and that other Ministry priorities are considered.
- Provide leadership and support to resource users and industries to reduce carbon emissions and increase carbon storage by undertaking afforestation, protecting natural heritage areas, exploring opportunities for forest carbon management to increase carbon uptake, and promoting the increased use of wood products over energy-intensive, non-renewable alternatives.
- Help resource users and partners participate in a carbon offset market, by working with our partners to ensure that a robust trading system is in place based on rules established in Ontario (and potentially in other jurisdictions), continuing to examine the mitigation potential of forest carbon management in Ontario, and participating in the development of protocols and policies for forest and land-based carbon offset credits.

Theme 3: Help Ontarians Adapt

MNR will provide advice and tools and techniques to help Ontarians adapt to climate change. Strategies include:

- Maintain and enhance emergency management capability to protect life and property during extreme events such as flooding, drought, blowdown and wildfire.
- Use scenarios and vulnerability analyses to develop and employ adaptive solutions to known and emerging issues.
- Encourage and support industries, resource users and communities to adapt, by helping to develop understanding and capabilities of partners to adapt their practices and resource use in a changing climate.
- Evaluate and adjust policies and legislation to respond to climate change challenges.

Comparing Various Approaches for Estimating Fire Frequency: The Case of Quetico Provincial Park

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Abstract

In this report, we compare approaches used to estimate the fire frequency for Quetico Provincial Park, Ontario, to highlight their advantages and associated challenges. Our objective was to augment resource managers' understanding of natural fire regimes to support forest and protected area planning and management. The approaches we used to estimate fire frequency were (1) survival analysis (Scoular 2008), (2) a pre-industrial context (PIC) historical analysis (Elkie et al. 2009), (3) a digital fire atlas analysis (Scoular 2008), (4) an empirical fire ecology study (Woods and Day 1977 a, b), and (5) landscape simulation modelling using the Boreal Forest Landscape Dynamics Simulator (BFOLDS) (Perera et al. 2008). This combination of approaches allowed us to compare the recent past (decades) to the long-term past (hundreds of years) in terms of the amount of stand-replacing fire that has occurred in Quetico's ecosystems. Landscape simulation modelling results of long-term fire return intervals without fire suppression were compared to empirical results from the actual (fire-suppressed) recent past to deduce the effects of fire suppression on the frequency of stand-replacing fire in Quetico Park.

Résumé

Comparaison de diverses approches pour évaluer la fréquence des feux : le cas du parc provincial Quetico

Dans le présent rapport, nous avons comparé les approches utilisées pour évaluer la fréquence des incendies dans le parc provincial Quetico, en Ontario, pour en dégager les avantages et les défis qui y sont liés. Nous avions pour objectif de fournir aux responsables de la gestion des ressources une meilleure compréhension des régimes des feux d'origine naturelle et d'améliorer la planification et la gestion des zones protégées et des forêts. Les approches auxquelles nous avons eu recours pour évaluer la fréquence des feux sont : 1) l'analyse de survie (Scoular 2008); 2) l'analyse historique dans un contexte préindustriel (Elkie et al. 2009); 3) l'analyse d'atlas des incendies numériques (Scoular 2008); 4) des études empiriques et écologiques des incendies (Woods and Day 1977 a, b); et 5) la modélisation de simulation des paysages à l'aide du Simulateur de la dynamique des paysages de la forêt boréale (*BFOLDS*) (Perera et al. 2008). La combinaison de ces approches nous a permis de comparer le passé récent (décennies) au passé à long terme (centaines d'années) quant au nombre de feux causant le remplacement des peuplements qui sont survenus dans les écosystèmes du parc Quetico. Les résultats de la modélisation de simulation des paysages à long terme des intervalles de retour des feux sans extinction ont été comparés aux résultats empiriques d'un passé récent réel (avec extinction des incendies) pour en déduire les effets de l'extinction des incendies sur la fréquence des feux de remplacement des peuplements dans le parc provincial Quetico.

Acknowledgements

Support for this research was provided by the Ontario Ministry of Natural Resources Climate Change Program under the auspices of CC-07/08-019. We are grateful to Paul Gray and Karen Hartley for reviewing earlier versions of the manuscript. We thank Trudy Vaittinen for layout and graphic design. Gratitude is also extended to Lisa Solomon and Andrea Allison of Quetico Provincial Park for their interest and support of this research.

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Contents

Introduction

Protecting ecological integrity is a principal objective in the management of provincial parks in Ontario (Statutes of Ontario 2006). Understanding ecological processes such as natural disturbance regimes is a potentially useful tool for park management planning. In addition, the *Fire Management Policy for Provincial Parks and Conservation Reserves* (OMNR 2008) promotes fire management planning for protected areas as a means to maintain and restore ecological integrity. Investigation of the natural fire regime and how it has changed is important for assessing the effects of ecosystem changes and for setting resource management objectives. Similarly, Ontario's *Crown Forest Sustainability Act* (Statutes of Ontario 1994) provides for the sustainability (long-term health) of Crown forests to be managed to meet social, economic, and environmental needs of present and future generations. In particular, Crown forests should be managed to provide for long-term health and vigour "*by using forest practices that, within the limits of silvicultural requirements, emulate natural disturbances and landscape patterns while minimizing adverse effects on plant life, animal life, water, soil, air and social and economic values, including recreational values and heritage values. 1994, c. 25, s. 2 (3).*"

Through forest management, emulation of natural disturbance and landscape patterns (or END) is one approach for conserving biodiversity[1]. END as a management tool has been comprehensively discussed recently (e.g., Klenk et al. 2008, Long 2009, Perera et al. 2004). Characterizing the appropriate disturbance regime (e.g., Bergeron et al. 2001, Girardin et al. 2006, Ter-Mikaelian et al. 2009) is a conceptual and practical challenge to implementing END, and projected influences of climate change on natural disturbance rates will only increase the complexity of this task (Ter-Mikaelian et al. 2009).

We examined various approaches for estimating the frequency of fire for this boreal to Great Lakes-St. Lawrence transition forest. Fire frequency refers to the number of fires that occur within a given time period. Fire frequency has been most commonly expressed in terms of mean fire interval and fire cycle. A fire interval is the expected number of years between two successive stand-replacing fires at any given location (Johnson 1979). A fire cycle is an area-based estimate of a fire regime expressed as the number of years required to burn an area equivalent to the study area (Heinselman 1973). Both of these fire frequency concepts were estimated in our study.

Quetico Provincial Park in Ontario, Canada, has a long history of fire frequency studies that make it a useful case study for addressing END in other forests. The approaches and measures of fire frequency gleaned from each were:

1. Survival analysis fire interval estimates based on a 1968 forest resource inventory (FRI) and a digital fire atlas (Scoular 2008).
2. A pre-industrial context (PIC) fire cycle estimate based on historical survey notes (Elkie et al. 2009) and the 1927 forest inventory (Ontario Forestry Branch 1927).
3. A digital fire atlas analysis fire cycle estimate (Scoular 2008).
4. An empirical fire ecology study by Woods and Day (1977a,b), which provided fire cycle and fire interval estimates.
5. Landscape simulation modelling. As part of the development of Ontario's *Forest Management Guide for Boreal Landscapes* (OMNR in prep.), landscape simulations using the Boreal Forest Landscape Disturbance Simulator (BFOLDS) were conducted to develop estimated ranges of natural fire interval variation for the study area.

[1] Condition 39 of the Declaration Order regarding the Ontario Ministry of Natural Resources' Class Environmental Assessment Approval for Forest Management on Crown Lands in Ontario.

This combination of approaches allowed us to ask the following questions:

- How does the recent past (decades) compare to the long-term past (hundreds of years) in terms of the amount of fire?
- How does landscape simulation modelling of long-term fire return intervals without fire suppression compare to the recent past, given 40 years of fire suppression?

Thus, our hypotheses were:

1. Stand-replacing fire frequency does not vary between a recent period (1963-2003) and the entire period of study (1668-2007).
2. Quetico Park's current fire frequency is an artifact of over 40 years of fire suppression.

The Study Area

At 475,782 ha, Quetico Provincial Park is the third largest wilderness-class Provincial Park in Ontario (Figure 1). Located in the 4W Pigeon River Ecoregion (approximately 48°N 90°W), Quetico lies in a transition zone between boreal forests to the north, mixed (Great Lakes-St. Lawrence) forests to the south and southeast, and Great Plains forests to the west and southwest (Kronberg et al. 1998). A 1966 Ontario Department of Lands and Forests (now OMNR) forest resource inventory (FRI) and a photogrammetric survey of the Park (Woods and Day 1976) indicate that boreal species such as jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* (Mill.) BSP), trembling aspen (*Populus tremuloides* Michx.), and paper birch (*Betula papyrifera* Marsh.) were dominant, comprising about 90% of Quetico's forested landscape. However, Elkie et al. (2009) found that between 1880 and 1920 forest stands that consisted of at least 40% red pine (*Pinus resinosa* Ait.) and/or white pine (*Pinus strobus* L.) made up 19% of the forested landscape. Based on the ecology of these species, it is likely that this composition was significantly influenced by stand-replacing and surface fires typical of these forest regions.

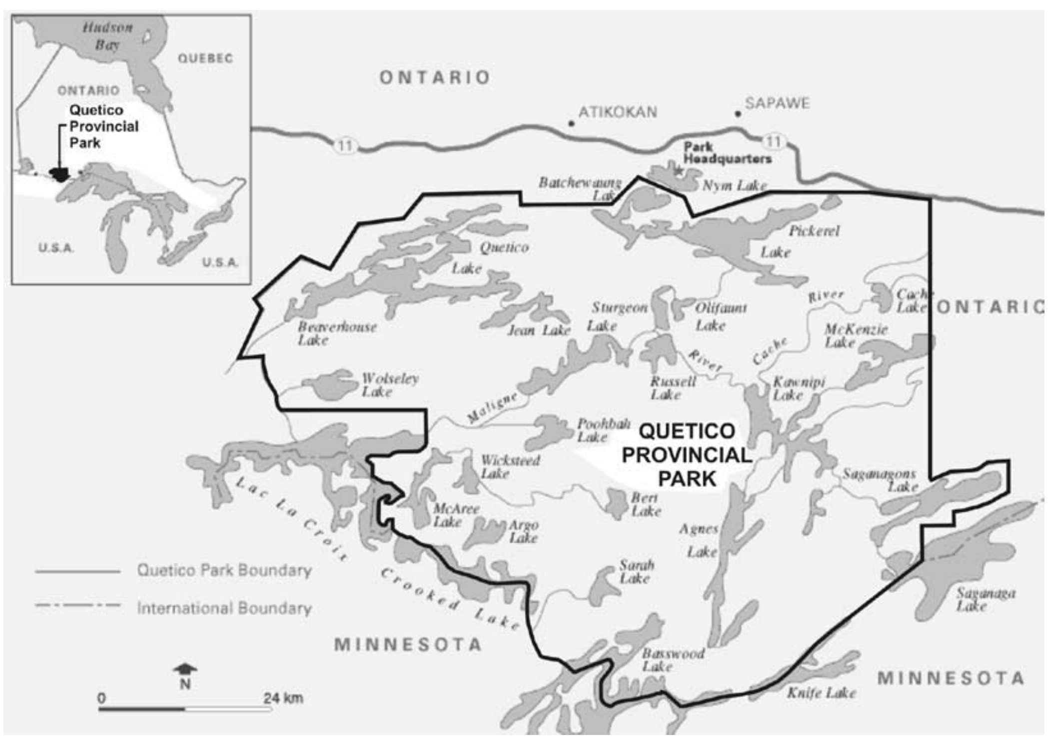

Figure 1. Location of Quetico Provincial Park, Ontario, Canada.

Parts of Quetico were logged from 1909 to 1946 and between 1961 and 1971 (Peruniak 2000). Prior to 1946, most logging was for square pine timber (i.e., white pine and red pine); while in the 1960s timber was mostly harvested for pulpwood (i.e., jack pine and black and white spruce (*Picea glauca* (Moench) Voss)). When added as attribute data to a geographic information system (GIS) database of the 1966 FRI, a provincial harvest ledger reveals that approximately 22,000 ha were cut from 1968 to 1971, and that areas outside of licensed timber berths were also cut during this period (Scoular 2008). After considerable controversy, logging inside the park was halted in 1971.

Although Ontario fire suppression legislation was first enacted in 1917 (*Forest Fires Prevention Act*), fire control was not effective until the late 1960s following advances in transportation and fire fighting technology (Ward and Tithecott 1993, Kasischke and Stocks 2000). Quetico is about 150 km from both the Thunder Bay and Dryden fire bases (MacLellan and Martell 1996), and it had its own fire base on Nym Lake for many years. Therefore, it has received direct and effective suppression over the years.

Prior to 1997, Quetico's policy was to suppress all detected fires. The 1997 Fire Management Plan (FMP) (OMNR 1997) included the reintroduction of fire using both prescribed burns and prescribed natural fires. Since the plan was approved, approximately 4,000 ha of the park have burned through prescribed and natural fires (OMNR 2009). Quetico's FMP was updated in 2009 to provide fire management direction for the next 10 years (OMNR 2009).

Findings of Quetico Fire Frequency Studies

1. Survival Analysis Study

Introduction

The goal of the survival analysis study was to characterize Quetico's fire regime. Survival analysis provides a way to estimate time-to-event data, where forest stand death due to fire is the event of interest. Stand-replacing fire frequency was estimated for the entire park over a long period (1668-2007) and for the period used during the BFOLDS landscape simulations that supported the review of Quetico's Fire Management Plan in 2009. Subsequently, the long-term past was compared to the recent past in terms of the amount of fire occurring in Quetico ecosystems. We tested the hypothesis that stand-replacing fire frequency did not differ between the entire period (1668-2007) and the recent period (1963-2003).

Our primary assumptions were:

1. All forest stands originated after fire. Although other disturbances such as insect epidemics, wind throw, and harvesting also initiate stand replacement, we feel that this assumption is valid because previous work identified 90% of Quetico's forest communities as being of fire origin (Heinselman 1973, Woods and Day 1977a).
2. Forest stand age was equated with time-since-fire (i.e., time of death is equal to time of post-fire community establishment/recruitment). This assumption is based on boreal tree communities typically recruiting within 1 to 4 years following fire (Heinselman 1996, Greene et al. 2004). Boreal forest fire return intervals also typically occur within the lifespan of post-fire cohorts and therefore understory cohorts rarely replace post-fire cohorts in the canopy (Masters 1990, Bergeron and Archambault 1993, Weir et al. 2000).
3. All fires were assumed to be stand-replacing. Although a limitation of our study, we feel that this assumption is valid as most area burned and therefore the majority of Quetico's forest communities originated from large, severe (i.e., stand-replacing) fires prior to 1891 (Elkie et al. 2009) and during 1895 (and/or 1894[2]) (Heinselman 1996), 1910, 1917 (Ontario Parks, no date) and 1936 (OMNR 1998).

[2] Oral tradition of Quetico indicates that a large fire burned in the southern portion of the Park in 1895. This is likely the fire to which Heinselman (1996) referred that burned in both Quetico and the Boundary Waters Canoe Area Wilderness in 1894 and/or 1895.

Methods

OMNR's 1968 FRI of Quetico provided a forest stand age-class (time-since-fire) distribution for the entire park. Aerial photography and ground verification field work for the FRI was completed in 1966. At that time, the oldest forest stand identified was 298 years, and thus it originated in 1668. Therefore, the period covered by the FRI was 1668 to 1966. The FRI of Quetico was geo-rectified and digitized using ArcGIS 9.2 GIS software to create a time-since-fire map for the entire park representing this period. OMNR's digital fire atlas was used to update the time-since-fire map from 1967 to 2007 and provide intervals between stand-replacing fires.

In this analysis, a complete observation was the interval between two fires. An incomplete observation was the time between a fire and the present with no subsequent fire event. Thus, forest stands on the time-since-fire map that have not burned since the year of the mapping are considered right-censored, or incomplete. Incomplete data represent a lower bound on the time-to-fire event estimate because all that is known is that these stands have survived unburned to their current age. We do not know when they will burn again.

We used non-parametric (Kaplan and Meier 1958) survival analysis (R Development Core Team 2007) to estimate survival functions, as well as corresponding mean and median fire intervals. We used non-parametric methods because comparative simulated samples confirmed that the empirical survival function was not a good fit to either the Weibull (Johnson 1979) or the negative exponential (Van Wagner 1978) theoretical fire models. The majority (91.8%) of the forest stands identified in the FRI had not burned a second time during the 1967 to 2007 period of the digital fire atlas, and therefore needed to be right-censored during subsequent analysis. A limitation of non-parametric survival analysis is that one cannot equate time-since-fire with fire interval; therefore, we were not able to isolate a pre-industrial time period.

We used the survivorship function to plot the probability of a landscape unit (FRI forest stand) being replaced by fire for each stand age (time-since-fire) class. The function was used to estimate mean and median intervals between two stand-replacing fires for any location in the park for 1668 to 2007 and 1963 to 2003. The statistical methods used to determine whether the survivor functions and therefore fire frequency for 1668 to 2007 versus 1963 to 2003 differed significantly are described in Appendix A.

Results

In the time-since-fire map (Figure 2), most of the area burned in the mid to late 20th century occurred in 1936 and 1995. In earlier decades, most stands originated after fires between the late 1800s and the early 1900s (Elkie et al. 2009), especially 1895 and/or 1894 (Heinselman 1996), 1910, and 1917 (Ontario Parks, no date). Stands with time-since-fire dates from 201 to 220 years likely originated after the 1803-1804 fires[3] (Ontario Parks no date).

The survival function can be estimated using the age at which a stand burned or the corresponding lower bound if the stand observation is right-censored. It can also reflect area weighting, which uses the area burned by the most recent fire on a forest stand to attach greater statistical importance to larger stand-replacing fires in the non-parametric estimation of the time-to-fire survival curve. Since our goal was to estimate the stand-replacing mean and median fire intervals in Quetico, which are point estimates, accounting for area burned was not considered necessary. However, to validate this choice the survival function for the entire park (the global survival function) was estimated with and without area weighting. The resulting estimated survivor functions were virtually identical for nearly 200 years. Beyond that stand age statistical precision deteriorates due to the small number of old growth stands. Since it would be unwise to interpret any apparent differences between the two estimates as important, subsequent survival functions were derived without area weighting.

3 Grace Lee Nute, "Voyageur's Highway" p. 61, J.D. Cameron, Hudson's Bay Company trader at Rainy Lake wrote that in 1803 and 1804, *"the whole country almost from one extremity to the other was in a continual blaze and stopped only by the snow of autumn."*

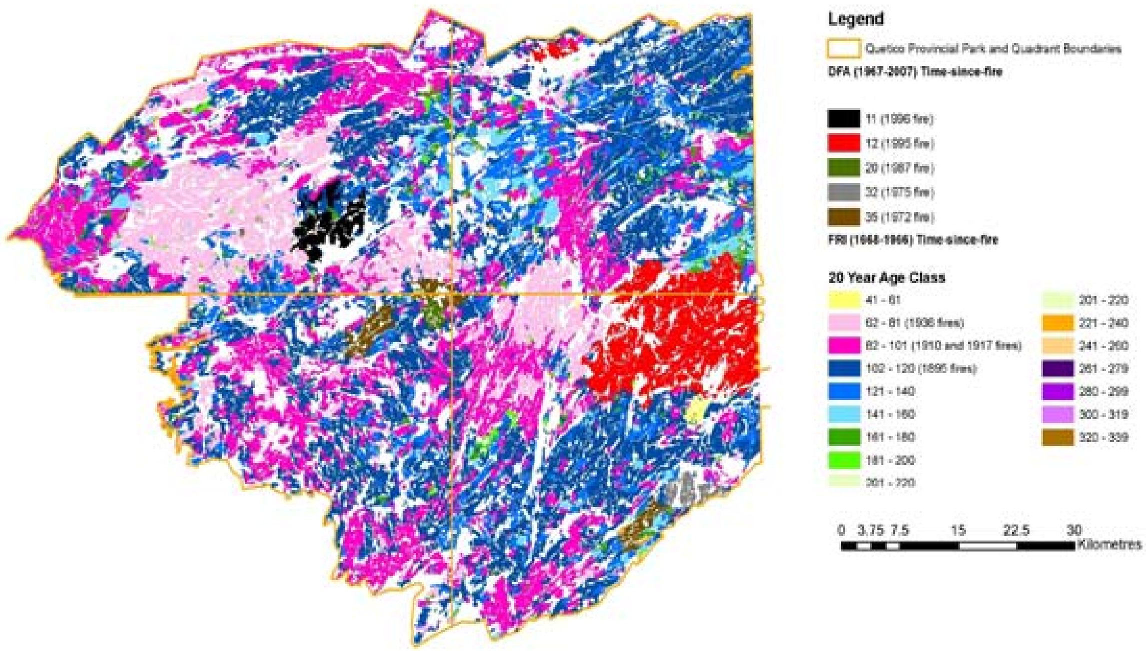

__Figure 2.__ A 1668 to 2007 time-since-fire map for Quetico Provincial Park created using the digital fire atlas (OMNR 1998) and the 1968 forest resource inventory (FRI). Note: the 1968 FRI provided historical fire years within 20-year age classes (for the period 1668-1966) whereas the digital fire atlas (DFA) provided the exact year of the fire (for the period 1967-2007).

In the survival function from 1668 to 2007 (Figure 3) there is a 5% probability that stands will burn before they reach 100 years of age (60% of the stands are younger than 100 years), a 20% probability that they will burn before 150 years, and a 40% probability that they will burn before 200 years. However, at 200 years only 46 of 7,493 stands remain. Therefore, the probability of stands not being replaced by fire should be regarded as an imprecise estimate beyond 200 years due to the small sample sizes for these old growth age classes.

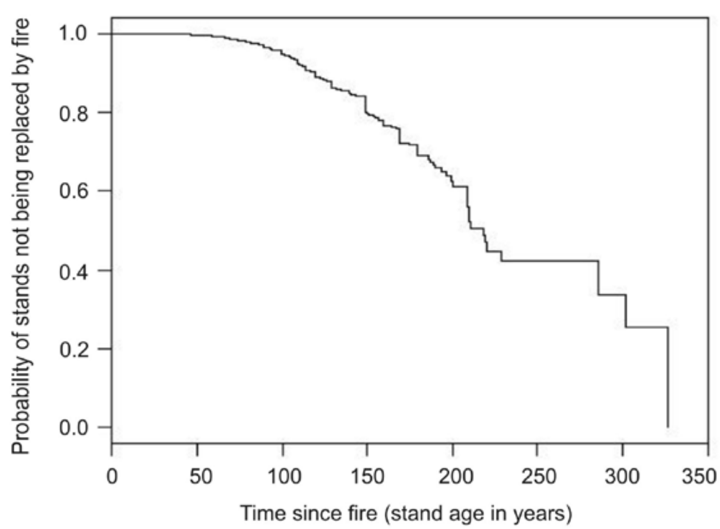

__Figure 3.__ The 1668 to 2007 survival function for forest stands in Quetico Provincial Park based on information from the digital fire atlas (OMNR 1998) and the 1968 forest resource inventory.

The mean and median fire intervals estimated from the Kaplan-Meier survival analysis are presented in Table 1. The mean and median fire intervals for the park from 1668 to 2007 were 230 years and 218, respectively. The mean and median fire intervals for the BFOLDS fire weather index period (1963-2003) were 201 years and 196 years, respectively. The mean and median fire intervals for the park without the 1995 Fire #141 were 318 years and infinity, respectively.

Table 1. *Fire frequency temporal variability estimated using survival analysis based on the digital fire atlas (OMNR 1998) and the 1968 FRI.*

Spatial Extent	Period	Mean Fire Interval (years)	Median Fire Interval (years)	Standard Error (years)	95% Confidence Interval
Entire park	1668-2007	230	218	7	216-244
Entire park (BFOLDS comparison)	1963-2003	201	196	6	189-213
Entire park (Without Fire #141)	1668-2007	318	N/A[1]	5	308-328

[1] N/A (not applicable) because the corresponding estimated survivor function does not decrease below 0.5, the median cannot be estimated.

For the results of the statistical approach used to determine significant differences between the survivor functions and therefore fire frequency for 1668 to 2007 versus 1963 to 2003 refer to Appendix A.

Discussion

We rejected our hypothesis that stand-replacing fire frequency did not vary between a recent period (1963-2003) and the entire period of study (1668-2007). We found considerable variation in fire frequency between the recent and the entire period (see Appendix A). The mean/median fire interval decreased and therefore the amount of fire increased during the recent period. However, the data weighted most heavily in the analysis came from the most recent period and therefore could have skewed the results. In particular, the 27,900 ha Fire #141 of 1995 in the southeast of the park significantly influenced the analysis. This fire burned about 5% of the park. The survival function estimates, and therefore the mean fire interval estimates, were primarily influenced by complete observations (fire intervals) provided by Fire #141. This fire provided 75% of the complete fire intervals in the survival analysis.

One difficulty in interpreting the data is the extreme influence of Fire #141 on the outcome of the analysis. On the one hand, the event is real and tangible in its effect. Conversely, if the lightning starting this fire had struck a few hundred metres to the west it would have landed in Bird Lake and the Fire # 141 would not exist. Then the whole analysis would have a different conclusion. Likewise, if Fire #141 had occurred later (e.g., after 2000), or if the arbitrary time periods used in the study had differed in duration or spacing, the temporal interpretation of the data would have differed. Equally, selection of a slightly different study area that incorporated land to the east (outside of Quetico Park) would have included extensive fires of the 1990s and thereby changed the results.

2. Pre-Industrial Context (PIC) Study

Land Survey Notes

Elkie et al. (2009) digitized original Ontario Land Survey notes from the pre-industrialized forests of northwestern Ontario (circa. 1880 to 1930) including the Quetico study area. They found that 33% of the lines surveyed in 1891 in the study area were recorded as recent or older burn (i.e., recorded as “brulé” and “old brulé”). In northeastern Ontario, fires from 1923 were recorded as older burn during surveys completed in 1950 (Elkie et al. 2009). It is generally accepted that when a surveyor recorded a line segment as burn, it represented a burn that occurred between 15 to 30 years prior to the survey (Jackson et al. 2000, Leadbitter et al. 2002). We used 23 years as a mid-point between this range of estimates to assume that any area recorded as recent and older burn had burned sometime during the past 23 years. We used this timeframe to estimate a fire cycle of 68 years, as follows:

$$\text{Annual burn rate} = \frac{\left(\dfrac{\text{survey line length recorded as recent and older burn}}{\text{total line length of all survey lines}}\right)}{23\ \text{(years)}}$$

$$\text{Fire cycle (years)} = \frac{1}{\text{annual burn rate}}$$

1927 Forest Inventory

The 1927 Rainy River Forest Survey (Ontario Forestry Branch 1927) classified the area now within Quetico Provincial Park according to existing forest types and age class conditions. A fire cycle was not calculated from this data set because the rate of human development between 1891 and 1927 made it impossible to separate human-caused from natural disturbances. In this inventory, 28% of the forest was identified as 41 to 60 years old, suggesting that a significant amount of disturbance would have occurred around the time of the 1891 surveys, thus corroborating the proportion of survey line observed as recent burn (33%) (Figure 4). It also hints at what could be a significant amount of disturbance resulting from settlement activities occurring at the same time.

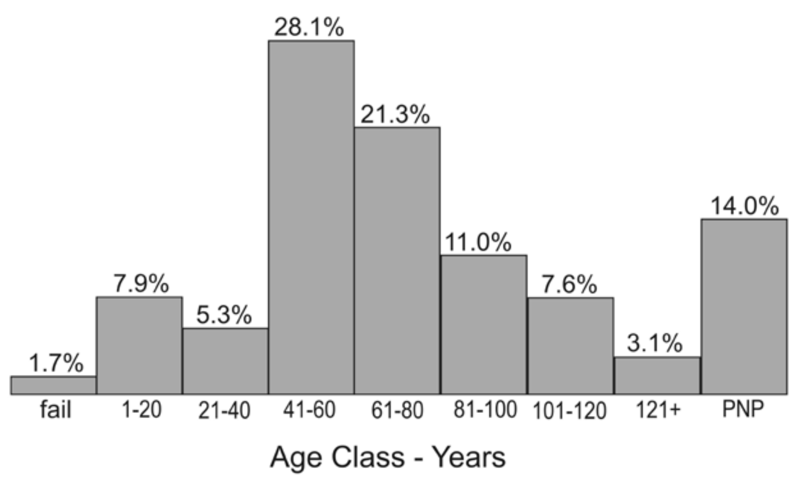

Figure 4*. The 1927 forest age class distribution for Quetico Provincial Park (FAIL = not free to grow, insufficient stocking at the time of survey, PNP = permanently non-productive, rock, muskeg, alder, etc.) (Ontario Forestry Branch 1927).*

3. Digital Fire Atlas Estimate

Introduction

Ontario forest fire history maps (1:500,000) were originally compiled by Donnelly and Harrington (1978). The mapping included all fires that occurred between 1921 and 1976 south of 52° North and north of the Canadian border, in an area referred to as the “Area of Undertaking” (all land and water within forest management unit boundary lines), that were greater than or equal to 200 ha. Donnelly and Harrington (1978) estimated that 5% of the total area burned is not included in this mapping because of missing fire reports and/or fire boundary mapping and non-reporting (especially in northern Ontario and during the Second World War). Additionally, they indicated that fires smaller than 200 ha likely accounted for 5% of the total area burned. Given these limitations, Donnelly and Harrington’s (1978) fire history mapping accounted for approximately 90% of the total area burned in this area of the province during the period of record.

In 1995, OMNR’s Forest Landscape Ecology Program updated the Donnelly and Harrington atlas as a digital database (OMNR 1998). To improve the spatial accuracy of the fire mapping, they used data from aerial photography and post-fire global positioning system (GPS) flyovers (1976-1995) and classified (supervised) satellite imagery (1973-1991). The final resolution of the mapping was 1 ha pixels. OMNR continues to update this data set via remote sensing and GIS technology.

The digital fire atlas used in this research covers the period 1921 to 2007. Limitations of this data set are that it excludes small fires (<200 ha) and does not document unburned areas within fire perimeters. For example, according to Song (2002), in 1995 approximately one-third of the area within Fire #141 in Quetico remained unburned.

Methods

The 1921 to 2007 digital fire atlas (OMNR 1998, updated) documents all recorded fires of 200 ha or more, including areas burned more than once. We used these data to estimate the fire cycle based on methods developed by Heinselman (1973). The fire cycle was calculated by dividing the number of years in the reference period by the total area burned during the reference period, multiplied by the study area size:

Br = (T/B)*A

where Br = burning rate, A = the park’s land area (373,451 ha), B = total area burned (94,906 ha), and T = time period (87 years).

In previous computations of fire cycle for Quetico Park, lake area located within burn perimeters was not accounted for. Since lakes cover 98,803 ha (or 21%) of Quetico’s area, not accounting for lake area would result in the fire cycle being underestimated by approximately 26%. Therefore, we removed lake area (ha) from total burned area prior to estimating fire cycles.

Results

The fire cycle for 1921 to 2007 estimated for Quetico Park based on fires documented in the digital fire atlas was 342 years. Two very large fires, one of 29,022 ha in 1936 (light pink area in Figure 2), and Fire #141 in 1995 (red area in Figure 2), account for most of the area burned during this period, and thus greatly influenced the calculated fire cycle.

Discussion

Other researchers have used a similar approach to estimate fire cycles. Ontario Parks has used Heinselman's (1973) "natural" (1727-1910) fire cycle estimate (100 years) in the past as a guide to reintroduce stand-replacing fire into the Quetico ecosystem because it provides an annual area burned target (L. Solomon, OMNR, pers. comm., 2008). However, most recently, Quetico's fire management plan (FMP) references Woods and Day's (1977b) 78 year natural fire cycle, although without any commitment to its emulation. If Ontario Parks elects to continue to use the fire cycle concept in fire management, our results can be used to evaluate the deviation from Heinselman's natural (pre-European settlement) fire frequency estimate. However, using Heinselman's (1973) estimate as an "ecological renewal" target (i.e., annual area burned) should be reconsidered in light of the temporal variability in fire frequency confirmed by the survival analysis estimates.

4. Quetico Fire Ecology Study

Introduction

Between 1975 and 1977, OMNR and Lakehead University collaborated to study the fire ecology of Quetico (Woods and Day 1975) to provide ecological information to support fire and vegetation management pursuant to Park Master Plan requirements (Smith and Elder 1975). Woods and Day (1975) documented their three study objectives as:

1. To photogrammetrically examine the present species composition and stand structure of the forests of Quetico Park
2. To examine the stand structure and ecological succession in jack pine and red pine forests in Quetico Park using field sampling
3. To locate, date, and map the unrecorded fires in selected study areas within the park

Methods

Woods and Day (1977a) inferred the age-class structure of Quetico's forests and therefore fire frequency from aerial photography, 1948 and 1966 FRI, tree cores, and mapping unrecorded fires using fire scar information.

Results

Woods and Day (1977a) estimated Quetico's "natural" (pre-European settlement) fire cycle to be 78 years and the natural mean fire interval to be 66 years (Table 2). These estimates were derived from stand-replacing and surface fires and therefore included fires of mixed severities (i.e., non-lethal, partially stand-replacing, and stand-replacing). Their study area covered 21% of the north-central part of the park (79,118 ha) and they predominantly

***Table 2**. Fire frequency estimates for Quetico Provincial Park by time period (Source: Woods and Day 1977a,b).*

Mean fire interval (Period)	Fire cycle (Period)
870 years (1850-1969)	78 years (1850-1920)
66 years (1870-1919)	200 years (1920-1977)
202 years (1920-1969)	

sampled red pine stands that may have originated from and been renewed by non-lethal fires. These stands were almost exclusively adjacent to waterways and thus not representative of the entire park. These data were not re-analyzed using current statistical methods and therefore confidence intervals are not available.[4] Woods and Day (1977b) also provided mean fire interval estimates for the major forest communities within Quetico (Table 3).

Table 3. *"Natural" fire frequency estimates for Quetico's fire-dependent forest communities* (Source: Woods and Day 1977a,b).

Forest community type	Mean fire interval estimate (range in years)
Jack pine	80-120
Black spruce	90-120
Red pine and white pine	175-250
Poplar	70-80

Discussion

Although the estimates by Woods and Day (1977a,b) characterize the natural mean fire interval for the major forest communities in Quetico, given that fire frequency varies geographically, these estimates should not be used as management prescriptions (e.g., timing and location of prescribed burns) for the entire park. For example, a black spruce forest community in the southern part of Quetico can have a very different fire frequency than a stand of the same composition in the northern part of the park. The large variation in fire frequency by forest community observed by Woods and Day (1977b) likely resulted from difference in species physiographic characteristics such as fire tolerance/resistance and adaptation as well as the sites that they occupy, rather than the spatial distribution of fire. For example, black spruce growing on bog and rich swamp wetland sites can escape burning for centuries, but jack pine/black spruce communities that occupy dry upland sites are subjected to relatively short fire return intervals. However, the fire frequency estimates do provide an excellent base for use in planning prescribed burn intervals for the area addressed by the study (i.e., the northcentral portion of the park).

5. Landscape Simulation Modelling

Introduction

Landscape simulation models can provide probability-based estimates about what might happen over a specific period and can provide estimates of the inherent variability and potential of a landscape. The Boreal Forest Landscape Dynamics Simulator (BFOLDS) (Perera et al. 2008) was used in developing the *Forest Management Guide for Boreal Landscapes* (OMNR in prep). Landscape disturbance and succession models simulate the adaptive cycles of landscapes (Gunderson and Holling 2002) as they might occur without human intervention and generate fire return interval estimates. The goal of the modelling exercise in this study was to simulate natural variation around a natural reference condition similar to a pre-industrial condition (PIC).

Methods

BFOLDS (developed by Ontario's Forest Research Institute's Forest Landscape Ecology Program) models stand initiating fire, succession, and post-fire transitions in boreal forests and was developed to explore potential fire regimes (see Perera et al. 2008). It is a grid-based, spatially explicit model with a simulation module for crown-fire regimes (FSM) and a vegetation transition module (VTM) that simulates forest development over time. BFOLDS

4 The data used in the 1977 studies could not be acquired. Bob Day (Lakehead Univ, retired, pers. comm., 2007) was unable to verify availability or location of original data.

simulates the fire regime and fire-induced forest cover dynamics at broad spatial and temporal scales (>10 million ha and >300 years), but uses a fine spatial scale (1 ha resolution) for some processes.

Using expert knowledge and published literature, those involved in developing *Ontario's Forest Management Guide for Boreal Landscapes* (OMNR in prep.) calibrated the forest succession, fuel types, soil moisture, and nutrient information for Ecoregion 4W to use for BFOLDS inputs. These inputs were modified by science and field practitioners throughout the development of the guide. Modifications were made to landscape dynamics (e.g., forest succession rules and disturbance sizes and cycles) and landscape condition (e.g., forest cover and age) inputs as well as to model mechanics (e.g., how BFOLDS simulated fire spread). Details of these BFOLDS inputs are provided by Elkie et al. (2009).

A median fire return interval layer quantifies the average period between fires under the historical or simulated fire regime. We used twenty 200-year simulations for the study area. After each replication, a total burn count raster data set was produced. These were summed for 20 simulations and divided by the total number of simulation years to estimate a mean fire return interval for each 1 ha pixel in the study area.

Results

The estimated median fire return interval for Quetico Park was 78 years (Table 4). The predominant median fire return interval across Quetico was 51 to 75 years, with somewhat higher intervals occurring in the west, on lake islands, and on the shores of lakes. The longest median fire return intervals of greater than 150 years occurred on islands in the northcentral area of the park (Figure 5).

Discussion

The landscape simulation results provide spatially explicit estimates for the fire return interval and its associated variability. This allows managers to examine what happened through historic reconstruction and explore the probability of any given outcome based on a range of simulated outcomes.

As an additional observation, the longest median fire return intervals occurred in areas with high concentrations of lakes, which likely restrict the spread of simulated fires and extend the time between events. Conversely, the shortest median return intervals occurred in areas with the lowest concentration of lakes. On the actual landscape, many of the areas with long fire interval are associated with magnificent old growth white and red pine stands. This is a similar observation to Bergeron and Brisson (1994) who hypothesized red pine at the northern edge of its range in Quebec was isolated to islands with less frequent and lower intensity fires than the mainland. The BFOLDS landscape simulation model only simulates stand killing fires and does not simulate low to medium intensity surface fires, which red and white pine (with thick bark) are well adapted to survive. This limitation in the calibration makes estimation of surface fires impossible, but one could hypothesize that areas of longer simulated fire intervals around lakes could have surface fires compatible with red pine communities.

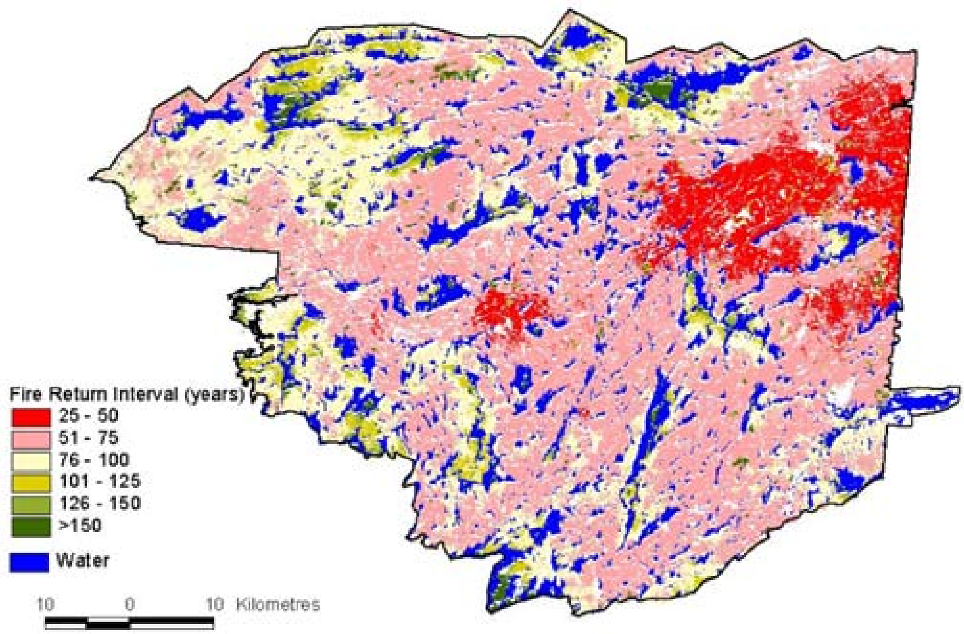

Figure 5. *Simulated fire return interval for Quetico Park, Ontario estimated using BFOLDS.*

Concluding Remarks

Variation in Stand-Replacing Fire Frequency Through Time

We compared the results of a variety of methods used to estimate fire frequency for one wilderness area with the purpose of highlighting the advantages and difficulties of each. This comparison allows for better understanding of variability in relation to the time period selected for observation and the approach used. Table 4 provides a comparison of the results and Table 5 identifies the limitations and strengths of each of the approaches discussed here.

Table 4. *Summary of fire frequency estimates for Quetico Provincial Park by study.*

Study	Fire frequency concept applied	Estimate	Assessment period
Survival analysis (Scoular 2008)	Mean fire interval	230 years	1668-2007
		201 years	1963-2003[2]
		318 years[1]	1668-2007
	Median fire interval	218 years	1668-2007
		196 years	1963-2003
Pre-industrial condition (Elkie et al. 2009)	Fire cycle	68 years	1880-1930
Historical reconstruction (Scoular 2008)	Fire cycle	342 years	1921-2007
Fire ecology study (Woods and Day 1977 a,b)	Mean fire interval	66 years	1850-1920
	Fire cycle	78 years	1850-1920
BFOLDS (Elkie et al. 2009)	Median fire interval	78 years	200-year simulations with 1966 FRI used to represent initial forest cover type and age

[1] Does not account for 1995 Fire #141
[2] BFOLDS fire weather index data coverage

Table 5. *A comparison of approaches used to estimate fire frequency in Quetico Provincial Park, Ontario: assumptions, advantages, and limitations.*

Approach	Assumptions	Advantages	Limitations
Survival analysis based on digital fire atlas and forest resource inventory (Scoular 2008)	All forest stands originated after fire: a. Forest stand age was equal to time-since-fire (i.e., time of death is equal to time of post-fire community establishment/ recruitment). b. All fires assumed to be stand-replacing. c. Stable climate and uniform site conditions throughout study area and over time (i.e., assumed spatiotemporal homogeneity).	Does not require fitting data to theoretical fire model (e.g., negative exponential or Weibull). Survival function/ probability of burning derived from empirical data. Covered entire area of Quetico Park. Covered long time period (1668-2007). Produces confidence intervals for fire frequency estimates.	Unlike assuming a negative exponential fire model, cannot treat incomplete observations (time-since-fire) as complete observations (fire interval) (Polakow and Dunne 1999, Scoular 2008). Only allows for comparison of fire frequency for different time periods/spatial partitions if one fire interval ends within period/area of interest (Polakow and Dunne 1999, Scoular 2008).
Assessment of pre-industrial condition using land survey notes (Elkie et al. 2009)	See a and b above.	Empirically observed.	Not universally available and covers only a short period. Not detailed and information is confined to transect lines.
Historical reconstruction using a digital fire atlas/stand origin map and the fire ecology study (Scoular 2008, Woods and Day 1977a,b)	The spatial extent of every fire identified was accurate.	Do not need to fit data to theoretical model (e.g., negative exponential or Weibull). Do not need to assume spatial or temporal homogeneity (i.e., probability distributions are the same for all regions or time periods). Simple computation Accurately documents size of fires >200 ha and their distribution in space and time; therefore characterizes the spatial and temporal variability of fire regimes.	Lacks statistical model to test hypotheses (e.g., differences in fire frequency among regions or time periods). Woods and Day's (1977 a, b) study covered only 21% of the park area and they sampled mostly red pine stands that may have originated from non-stand-replacing fires. Evidence of fires partially erased by subsequent fires; therefore data not always available. Requires detailed data about fires (e.g., either annual fire maps (digital fire atlases) or time-since-fire maps based on air photos, stand origin, and fire scars to determine the boundary of every historical fire).
Simulation modelling using BFOLDS (OMNR in prep.)	Provides information about potential fire regimes given various inputs including weather, succession, and abiotic conditions. The model is well tested.	Can simulate fire and forest succession spatially over regional scales (millions of hectares) for long periods (100s of years).	Requires users to clearly understand assumptions and model mechanics. Uses actual weather from past 40 years to created simulated weather sequences. Does not simulate climate change unless directed through assumptions (e.g., simulate more years like 1976, fewer years like 1999). Complicated software that requires highly trained operator.

Quetico is remarkable in having had so many different estimates of fire activity. Comparing these estimates is not easy and requires caution. The studies differ in field data collection methods, areas studied, measures of fire frequency applied, and time span (Table 4). Whether one examines fire cycle, mean fire interval, or median fire interval, Woods and Day's estimates for the 1850 to 1930 period, the PIC estimate, and the BFOLDS simulation results are in broad agreement. The fire cycle is estimated to range between 68 and 78 years (Woods and Day 1977a, Elkie et al. 2009). The mean fire interval is estimated at 65 years (Woods and Day 1977a) and the median fire interval at 78 years (Elkie et al. 2009).

Scoular's (2008) method highlights the utility of older FRI data in these studies. This study allows consideration of a much longer time period, but also differs in methodology and study area from that used by Woods and Day (1977a). The fire regime metrics for 1668 to 2007 are very different from Woods and Day's non-suppression estimate and the simulated estimate, with a mean interval of 230 to 318 years and a median interval of 218. The estimate suggests much less fire during a period that extends back into the little ice age and includes the peak of the fur trade industry (1786-1940), which altered fire rates as a result of human activity in the area (Fritz and Suffling 1993). Scoular's fire cycle (digital fire atlas) estimate for the period 1921 to 2007 was 342 years. In agreement with this but differing in methods, Scoular's survival analysis estimate for the fire suppression period of 1963 to 2003 also generated a long mean fire interval of 201 years.

Effect of Fire Suppression on Quetico Park's Current Fire Frequency

Many authors have hypothesized that fire suppression has influenced the fire frequency (annual area burned) of Canadian boreal forests (Cumming 2005, Martell 1994, Martell 1996, Stocks 1991, Ward and Tithecott 1993, Weber and Stocks 1998, Li 2000, Ward and Mawdsley 2000). Others have suggested that fire suppression has had minimal influence on fire frequency, especially prior to the use of water bomber tankers beginning in the 1970s (Miyanishi and Johnson 2001, Miyanishi et al. 2002, Bridge et al. 2005, Ter Mikaelian et al. 2009). Several fire frequency studies in and around Ontario reported no change in the fire cycle since the 1920s (Bergeron and Archambault 1993, Bridge et al. 2005, Heinselman 1973, Woods and Day 1977a). Ter Mikaelian et al. (2009) question whether fire frequency is changing under the influence of climate or suppression, and suggest that the future fire regime will be characterized by long periods of fire quiescence and then multi-year outbreaks of fire. This was also postulated by Suffling and Speller (1998).

Analysis of forest fire suppression records for Quetico indicates that 502 lightning-caused fires occurred between 1963 and 2002. Approximately 170 of these fires received some form of active suppression. During this period only 11 natural (non-suppressed) fires grew to a final size of between 10 and 1,000 ha.

A suppression era estimate is not recommended for use in this designated wilderness area. The long interval indicated by Scoular's (2008) data for the last half of the little ice age, averaged with the period afterwards is scarcely more appropriate because the climate has warmed and we do not have a long modern track record of unsuppressed fire to which we can refer. All that we know with certainty is that prevalence of fire fluctuates wildly over many decades and this makes fixing on a target very difficult and possibly inappropriate. Survival analysis mean fire interval estimates were derived to provide context for the comparison between "natural" fire frequency estimates of previous studies (Heinselman 1973, Woods and Day 1977a) and the BFOLDS estimates. We hypothesized that the park's current fire frequency is an artifact of over 40 years of fire suppression. The BFOLDS median fire interval estimates were derived from fires that were not suppressed (i.e., the simulations were developed to estimate the range of natural variation) whereas Scoular's (2008) research estimated mean fire intervals from both fires that were suppressed and those that were allowed to burn. Therefore, the influence of fire suppression on the park's fire frequency can be inferred. The actual long-term (1668-2007) mean fire interval estimate derived for the entire park using survival analysis was 230 years whereas the simulated natural median fire interval was 78 years, suggesting that fire frequency has been influenced by fire suppression.

Recommendations

Depending on the objectives (e.g., emulate current natural conditions, emulate historocal natural conditions, maintain current levels of old growth, etc.) of a management plan for a wilderness area, we feel that there is no right or wrong answer when choosing a fire regime to emulate. Depending on the data source and analysis method we used, both the fire cycle and fire interval varied greatly, possibly due to:

- incomplete or conflicting analysis techniques
- incomplete or conflicting data
- recent fire suppression
- varying anthropogenic influences
- potential long- and short-term changes in climate
- non-detected burns

This study also provides insight to the situation in forests outside Quetico that use management to emulate natural disturbance and landscape patterns (or END) to conserve biodiversity. Our work demonstrates variability in the amount of burning within the Quetico study area throughout the past 350 years in relation to human influences and possibly with respect to climate and endogenous, regional changes in fuel. Climate change projections for the Quetico Park area show some of the most significant increases in temperature in Ontario (Colombo et al. 2007). Future studies should correlate fire frequency data with weather data (e.g., fire weather indices) to confirm the influence of recent climate variation on the temporal variability of fire frequency (Suffling 1992, Lauzon et al. 2007). Historical variability combined with climate change could increase the uncertainties associated with using END as a management tool. In particular, choosing a fire regime to emulate will require a discussion of the temporal variability, as demonstrated here. Management objectives should be reviewed and analyzed and a fire regime that best achieves these objectives while contributing to ecological integrity adopted.

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Appendix A: A Technique to Compare Stand-Replacing Fire Frequency in Overlapping Time Periods

A primary goal of this study was to compare the frequency of stand-replacing fire on any particular forest stand for the entire time period covered by the study data (i.e., 1668-2007) and the corresponding distribution of fire intervals for the shorter time period of 1963-2003. If the specified time periods do not overlap, the log-rank test (Matthews and Farewell 2007) can be used to compare the time periods directly. In this case, the shorter time period (1963-2003) is a subset of the other (1668-2007), and therefore the standard log-rank test is not applicable. To compare fire frequency distribution for the two time periods, we used an atypical statistical approach.

First, Kaplan-Meier estimates of the underlying survivor functions for these two time periods were obtained. These estimates are plotted in Figure A1. The fact that the estimate corresponding to the entire time period (solid line) is always greater than the estimate for the more recent 40-year period (dashed line) strongly suggests that the survivor function for the period 1963-2003 differs from that based on the full time span of 300+ years. The nature of these differences is perhaps best reflected in the corresponding point estimates of the mean and median fire intervals (i.e., 201 and 196 [1963-2003] versus 230 and 218 years, respectively). These comparisons are illustrated in the estimates graphed in Figure A1, since the estimated mean fire interval corresponds to the area under the survivor function, and the estimated median is the stand age at which a horizontal line representing a probability of 0.5 intersects the estimated function. Clearly, the area under the survivor function (estimated using only data from the 1963-2003 sample) is less than the corresponding area based on the entire sample for 1668-2007 (201 versus 230 years). Likewise, by drawing a horizontal line on the graph at a vertical height of 0.5, it is evident that the stand age for the estimated median fire interval based on the 1963-2003 data is less than the corresponding stand age for the estimated median fire interval based on all the data (196 versus 218 years).

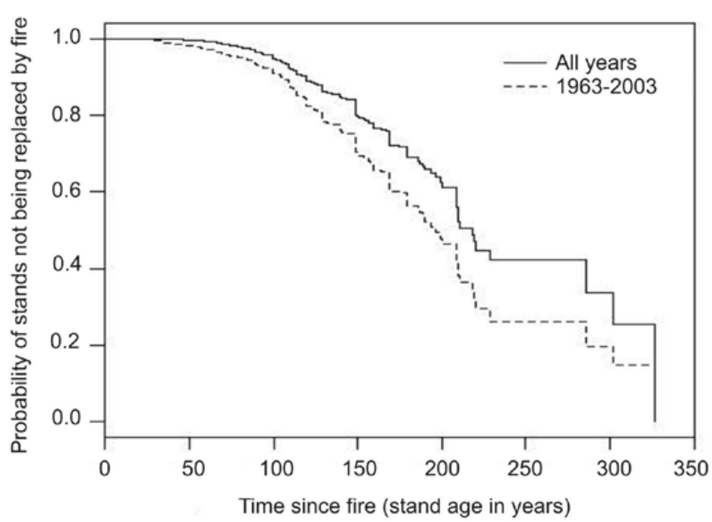

Figure A1. *Probability of stands not being replaced by fire in Quetico Provincial Park, Ontario.*

Since both samples involve the same 615 forest stands subjected to stand-replacing fires, we probed the specific calculations involved in the Kaplan-Meier estimate in more detail to understand how and why the two estimates differ. A key calculation is the nonparametric estimation of h_j, the conditional hazard (the probability of any given location within the study area being burned in a stand-replacing fire) of a stand-replacing fire at j years. The estimate of h_j is a simple ratio:

$$\frac{\text{number of forest stands replaced by fire at age j years}}{\text{total number of forest stands observed to attain j years}}$$

The count in the numerator of this fraction is known as the 'event count at stand age j', whereas the total in the denominator is known as the 'risk count at stand age j'. Since the event count is included in the risk count, this conditional probability estimate (a fraction) will always be a value between 0 and 1. Subtracting this conditional probability estimate from 1 gives us the estimated conditional probability that a forest stand, which is exactly j years old, will not experience a stand-replacing fire at age j. And the value of the Kaplan-Meier estimate at any particular stand age (e.g., r years) is the product of the estimated values of all these conditional probabilities of no stand-replacing fire at all younger stand ages 1, 2, ..., r.

In the study data set, the same event counts occur in each of the time periods of interest. Therefore, any differences between the two Kaplan-Meier estimates must arise because the associated risk counts derived for the two time periods are different. Figure A2 illustrates just how different these risk counts are. Again, the solid line indicates the risk counts at each stand age in the data from 1668-2007. Initially, all 7,493 stands in Quetico that are a year old are at risk of experiencing a stand-replacing fire. As stand age increases, the risk counts decrease, either due to an observed stand-replacing fire or because the interval of observation terminates in 2007 without a stand-replacing fire (i.e., the observation for that particular stand is incomplete, a right-censored lower bound on the stand-replacing fire event). Contrast the solid line with the effect of restricting the sample information to the more recent time period of 1963-2003. In this case (dashed line) the risk counts for young stand ages are quite low, and they increase to a maximum of roughly 4,700 forest stands around age 75, then decrease in a pattern

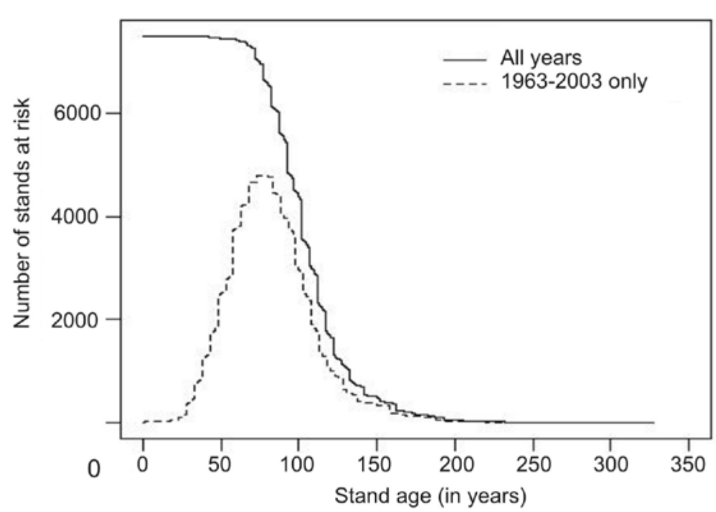

***Figure A2**. Number of stands at risk of burning in Quetico Provincial Park, Ontario.*

that approximates the decline in the corresponding risk counts from the full set of data. Since the event counts are always the same at any particular stand age, but the risk count is always lower in the data from the restricted sample, it follows that the estimated conditional probability of a stand-replacing fire will always be larger in the restricted sample than in the full sample. That this is indeed the case is illustrated in Figure A3, where we have plotted the ratio of the two estimated conditional probabilities of a stand-replacing fire (1963-2003 versus 1668-2007) against stand age. Since the plotted ratios (points) are always 1 (the horizontal dashed line) or larger, the estimated conditional probability of a stand-replacing fire appears to be uniformly greater when based solely on the data in the restricted sample (1963-2003) than when based on the entire time period covered by the study sample (1668-2007). Therefore, in recent history (1963-2003) the conditional probability of a stand-replacing fire at nearly every stand age is greater than the conditional probability estimate for the 1668-2003 period.

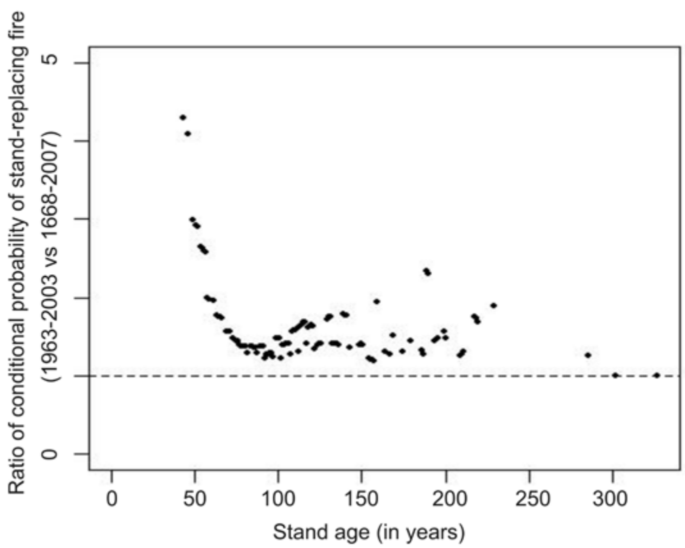

Figure A3. *Ratio of the conditional probability of fire (1963-2003 vs 1668-2007), Quetico Provincial Park, Ontario.*

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