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May 2003

Published: 20 August 2003

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Effects of fire, logging and settlement on the boreal forest landscape in Ontario

by

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May 2003

EXECUTIVE SUMMARY

While it may be commonly accepted that human disturbances by logging and agricultural settlement would differ from natural disturbances in their impacts on the landscape, few empirical studies have directly investigated these impacts, particularly in the boreal forest. Thus, the objectives of this study were: 1) to investigate the landscape age distributions and disturbance cycles resulting from a combination of natural disturbance (primarily wildfire) and logging as well as each disturbance type alone; and 2) to compare the effects of logging and settlement on the spatial age mosaic of the landscape. The study area was the Gordon Cosens Forest (GCF) in the southern boreal region of Ontario that has been logged continuously since 1923 and the corridor bisecting the GCF that was settled in the early 20th century but now largely abandoned and regenerated to forest. We used a 1996 forest resource inventory and fire data for 1920-1995, both spatial data bases. For the first objective, we calculated maximum likelihood estimates (with 95% confidence intervals) of disturbance cycles for the GCF, separating the effects of fire and logging. For the second objective, we compared sizes and shapes of polygons between the settlement corridor and the commercially logged GCF as well as temporal changes in polygon sizes and shapes between the productive forest portion of the settlement corridor and the logged portion of the GCF. Polygon shape was measured by perimeter-to-area ratio.

The time-since-disturbance distribution that includes both fire and logging shows a significant increase in disturbance cycle around 1860 from 32 (29 to 35) years to 250 (235 to 266) years with no significant change coincident with the start of logging in 1923. However, the time-since-fire distribution obtained by assuming that logging had not occurred (i.e. dating all stands to their fire origin year) indicates two significant changes in fire cycle. The estimated fire cycles are: 32 (26 – 39) years prior to 1850, 82 (76 – 88) years for 1850-1899, and 1,598 (1,356 – 1,901) years for the post 1900 period. The longer estimated disturbance cycle for the most recent epoch of 1,598 years with no logging versus 250 years with logging indicates the impact of logging on decreasing the disturbance cycle. The rate of logging has increased steadily since 1923; the rate for the most recent 10 years of data (1987-96) would give a rotation (i.e. disturbance cycle due to logging) of 100 years. Although the last large fires in the GCF occurred in 1923, more recent large fires in the region suggest that such fires are still likely to occur in the GCF. Furthermore, with less than half of the productive forest area of the GCF logged since 1923, the landscape age distribution of the GCF strongly reflects the influence of both fire and logging.

The landscape resulting from settlement has a much finer scale spatial age mosaic than that resulting from commercial forestry. Polygons are significantly smaller and more complex in shape in the corridor reflecting the smaller sizes of homesteads that were settled compared with the much larger simpler shaped clearcuts occurring in the GCF. Although the areas that regenerated after farm abandonment now form fairly continuous forest, they clearly reflect the finer scale pattern of land allocation and abandonment in their age mosaic. Thus the landscape patterns created by logging and settlement differ significantly from each other and also from that resulting from natural disturbance.

ACKNOWLEDGEMENTS

We gratefully acknowledge the Ontario Ministry of Natural Resources for the use of their Forest Fire History Atlas database and Tembec Forest Resource Management for the use of the 1996 Forest Resource Inventory database as well as all of the supplementary data we requested. We particularly thank Ken Durst and his colleagues at the Spruce Falls Woodlands Office of Tembec for their logistical support; without their cooperation, help and patience in answering our endless questions concerning the FRI and their forestry operations, this project would not have been possible. We also acknowledge Tara Tchir and Rebecca Ritson-Bennett for data collection and Adriana Rodriguez for her invaluable part in the Arc/Info manipulation and analysis of the FRI and Fire Atlas databases. Funding for this project was provided by the Sustainable Forest Management Network.

INTRODUCTION

Natural and anthropogenic disturbances produce different age distributions and spatial age mosaics on the boreal forest landscape. Furthermore, the two dominant human disturbances in the southern boreal forest, settlement and logging, have different impacts on the forested landscape. Few, if any, studies have made comparisons of the effects of these different disturbances on the landscape and, in particular, on the boreal forest. Therefore, the objective of this study was to investigate the effects of natural (wildfire) and human (settlement and logging) disturbances on the boreal forest in an area where all three disturbances are occurring. Since areas of settlement are distinct from areas leased for commercial forestry, the first part of the study was to compare the impacts of natural disturbance (predominantly wildfire) and logging on the forest age distribution and resulting disturbance cycle of a large commercial forestry lease area and the second part compared the spatial age mosaic of this forestry lease area with an adjacent area of settlement.

Forest management often uses the idea of a regulated forest to provide sustainable production of wood products. Thus, the landscape is seen as made up of units of different ages. The objective of management is to regulate the forest ages so that the proportion in each age class is the same, thus producing a constant proportion of the landscape available to be cut in each time period as indicated in Figure 1a.

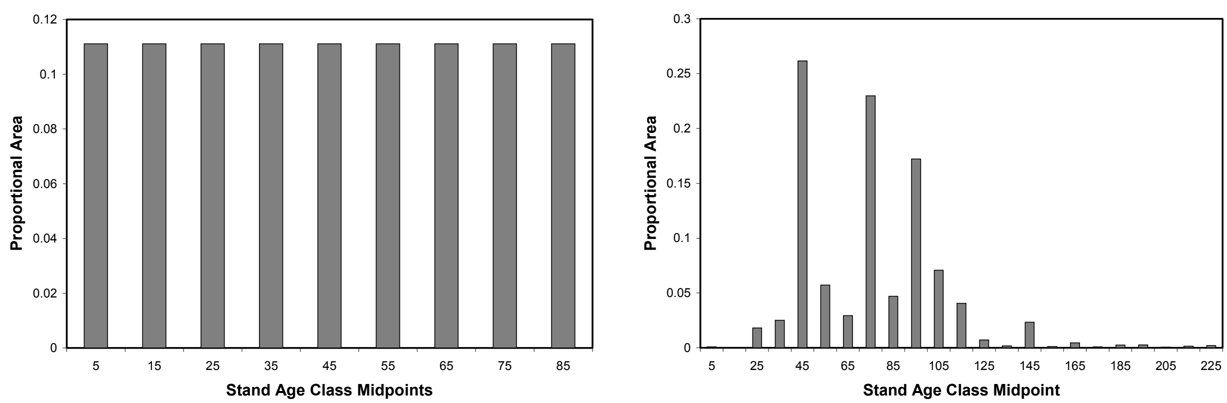

Figure 1. a) Age class distribution for a regulated forest with a rotation of 90 years. b) Age class distribution for Prince Albert National Park that is subject to wildfires but not to harvesting. Data from Weir et al. (2000).

The idea of a regulated forest developed in a European landscape which consisted of small, often even-aged plantations of similar composition, growth and yield of wood, scattered throughout a generally cultural landscape. Most North American forests are different from this model in a number of ways. First, they often consist of large contiguous forests of native species that have not been planted but result from natural regeneration. Second, not all of the forested landscape is productive and subject to forest management (e.g. poorly drained areas of muskeg).

Third, due to the large areas of contiguous forest, all of the productive forest may not be equally accessible. Finally, natural disturbances, particularly wildfire and insect outbreaks, are still significant aspects of the forest environment.

In recent decades, the idea of a fully regulated forest has been replaced by a more informal and complex management for multiple objectives that makes optimization of all objectives difficult, if not impossible. However, the simple idea of a fully regulated forest is still presented as the norm, particularly by those proposing the idea of ecosystem management by emulating natural disturbances (Hunter 1993; Bergeron et al. 1999). This idea in ecosystem management is that forest management practices should attempt to emulate the variation of natural disturbances such that forest harvesting would produce age distributions similar to those created by natural disturbances as illustrated in Figure 1b. The assumption here is that sustained yield forestry would inevitably create the unnatural age distribution of Figure 1a by removing the old age tail and making all age classes on the landscape represented by similar areas.

What has generally been lacking in this discussion is empirical evidence of the landscape age distribution actually produced by logging over a complete rotation period in a forest still subject to natural disturbance. In the North American boreal forest, sustained yield forestry generally started in the 1950's so most of the forests would not yet be expected to be fully regulated. In addition, earlier cutting would have followed rules of convenience and forest maturity, and changes in markets and technology would have led to differences in cutting rates and practices. An important assumption of the idea of emulating natural disturbances is that natural disturbances (i.e. wildfires) will be replaced by forestry practices (i.e. logging). However, the experiences of recent decades suggest that this may not yet be the case in the boreal forest (Bridge 2001) and that the current commercial forest is a product of both natural disturbance and logging. The availability of data for a large (1.7 million ha) area in the boreal forest that has been logged continuously since 1923 allowed us to test some of these assumptions. Thus, the **first objective** of this study was to determine the forest age distribution resulting from both wildfire and logging and to separate the effects of these two disturbances on the distribution.

A second major human disturbance in the southern edge of the boreal forest is forest clearance for agricultural settlement (Fitzgerald 1965; McDermott 1961; Beattie et al. 1981). The landscape resulting from this disturbance would be expected to differ from that resulting from commercial forestry. Settlement landscapes are determined by: 1) land surveying systems that produce given sizes and shapes of homesteads; 2) settlement plans and policies that dictate the amount of land that must be cleared and cultivated annually (Allen 1889; Algoma Central 1913; McDermott 1961); and 3) human activities on cleared land which increase the possibility of further subdivision of the landscape. On the other hand, commercial forest landscapes in the boreal forest are a result of: 1) large-scale clearcutting; 2) tree planting or natural regeneration of logged areas with no further land use that may lead to subdivision into smaller areas; and 3) management objectives that increasingly aim to imitate natural disturbances (e.g. Ontario Crown Forest Sustainability Act 1995). These different policies and practices for the two land uses would be expected to result in differences in the sizes, shapes and ages of the forest landscape mosaic.

Currently, there are few direct comparisons of the impacts of settlement and logging on the forest landscape (but see Drapeau et al. 2000). Although many studies focus on these land uses, they generally: a) discuss *either* forestry *or* settlement over time (e.g. Simpson et al. 1994; Reed et al. 1996; Staaland et al. 1998) but not both; b) make comparisons of logged and fire-disturbed landscapes (e.g., Carleton and MacLellan 1994; Gluck and Rempel 1996; Wallin et al. 1996); or c) examine one or several landscapes characterized by combined land uses (e.g. Turner and Ruscher 1988; Zipperer et al. 1990; Ericsson et al. 2000). Therefore, the **second objective** of this study was to investigate the different landscape patterns resulting from commercial forestry and agricultural settlement by comparing the sizes, shapes, ages, and proportions of cleared and forested patches in two closely adjacent landscapes, one dominated by logging and the other by settlement, with wildfires occurring in both.

METHODS

Study Area

The 1.9 million ha study area in northeastern Ontario (Figure 2) consists of the Gordon Cosens Forest (GCF), a 1.7 million ha area located from 81°40' to 83°W and 48°to 50°N at approx. 220 m above sea level and a 0.2 million ha corridor of roads, towns and agricultural settlements that bisects the GCF into a north and south section.

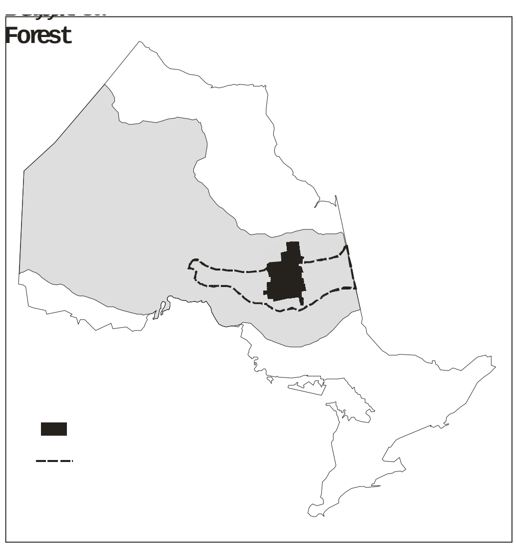

Figure 2. Map of the study area indicating its location within the Great Clay Belt and the boreal forest region of Ontario.

The study area is located mostly within the Great Clay Belt, an area of glacial lacustrine clay and clayey till deposits overlying the old rock surface of the Laurentian Shield. The topography of the Clay Belt is level to gently rolling plain, occasionally broken by rock hills and promontories of the surrounding Shield. The soils range from humo-ferric podzols in the southern portion of the GCF to gleysols and organic fibrisols and mesisols in the north, all with significant stony and lithic phases (Canada Department of Agriculture 1972; Clayton et al. 1977). The region has short, moderately warm summers (mean July temperature of 17° C) and long, very cold winters (mean January temperature –18.5°C) with a frost free period of 70-80 days. Annual precipitation averages 861 mm (Environment Canada 2002). The study area is within the southeastern edge of the boreal forest and consists of 75% conifers (primarily *Picea mariana* (Mill.) BSP., *Abies balsamea* (L.) Mill., *Larix laricina* (Du Roi) K. Koch and 25% hardwoods (mainly *Populus tremuloides* Michx. and *Betula papyrifera* Marsh.). *Pinus banksiana* Lamb. occurs on occasional outcrops while *Thuja occidentalis* L. is common along river banks.

The GCF, which has never been settled, is primarily crown land that is leased under a Sustainable Forest Licence (SFL), from the Ontario provincial government to Spruce Falls Inc. (a subsidiary of Tembec Inc.) for forest harvesting. However, one portion of the GCF comprising 75,072 ha was a freehold (patent) until 1998 at which time the land was returned to the province as crown land in exchange for an equivalent area as freehold within the southern portion of the GCF. The current annual allowable harvest is approximately 1.2 million m^3 of conifer and 400,000 m^3 of aspen (*Populus tremuloides*). Approximately 0.6 million ha have been logged since 1923 and no area has been logged more than once. The current management objective is a rotation of approximately 100 years (i.e. to harvest 1% of the GCF each year).

Initially, the logging was performed to supply the pulp mill at Kapuskasing (Spruce Falls 2001). In addition to the pulp mill which has continued to produce to the present, the company also ran a sawmill that produced kiln-dried studs from 1973 to 1987. Although harvesting has been continuous since 1923, methods of harvesting have changed over time with wheeled skidders replacing horses in the mid 1960s. The introduction of thermomechanical pulp in 1976 improved efficient utilization of wood resources. During the 1980s, harvesting operations became highly mechanized with the use of feller bunchers, stroke delimbers and high floatation skidder tires. Currently, much of the fiber used to supply the pulp mill comes from sawmill chips. Such changes in technology and operations would have affected not only the rate and environmental impact of harvesting but also the selection of sites for harvesting. For example, initially harvesting was generally restricted to sites close to rivers for transport of the logs; however, such constraints were removed once logging trucks became the main form of transport.

The settlement corridor bisecting the GCF includes the town of Kapuskasing as well as other small settlements along a main railway and highway (Figure 3). Agricultural settlement began after the completion of the railway in 1913 and was promoted by government plans in 1917 and 1932-33. These promotion schemes failed shortly after being implemented due to the harsh climate, distance from markets, poor soil drainage, and the appeal of forestry and mining industries (Troughton 1983). The resulting farm abandonment (Figure 4) is similar to the experience of other marginal frontiers (Beattie et al. 1981; Ihse 1995).

Figure 3. Small town (left) and farm (right) in the settlement corridor of the study area in northern Ontario.

Figure 4. Abandoned farm (left) and formerly cleared agricultural land regenerated to forest following abandonment (right) in the settlement corridor of the study area in northern Ontario.

Data Sources and Analyses

The data used came from Ontario's Forest Fire History Atlas (Ontario Ministry of Natural Resources 1998) and the 1996 Forest Resource Inventory (FRI) produced by Spruce Falls, Inc. These are both spatial data bases and all spatial analyses were done using Arc/Info. The Fire History Atlas includes data on all fires >300 ha for the period 1921-1995. The ages and stand type classifications in the FRI are based on the Ontario Ministry of Natural Resources codes (Ontario Ministry of Natural Resources 1986). The areas in the GCF classified as productive forest comprise 1,496,720 ha (87% of the 1,712,471 ha GCF) with the remaining 13% classified as muskeg, brush and alder, water, etc. (Table 1). In the settlement corridor, the productive forest area is 145,986 ha (81%) with the remaining categories comprising 34,143 ha (19%). The year of origin is available only for productive forest areas; hence, only these areas could be used for age distribution analyses. Also, the FRI data base was missing stand origin years (given as 0 in the data base) for polygons accounting for 60,068 ha (4% of the productive forest). These areas were also not included in the age distribution analyses.

Table 1. Percentage land cover of the Gordon Cosens Forest (GCF) and the settlement corridor classified by Ontario Ministry of Natural Resources (OMNR) code. Several of the original OMNR codes have been combined for simplification; e.g., the Muskeg classification includes both 'Open Muskeg' and 'Treed Muskeg'.

	% of total area	
	Settlement corridor	**GCF**
Productive Forest	**81.05**	**87.40**
Brush and Alder	**4.28**	**3.99**
Muskeg	**3.85**	**5.13**
Water	**3.24**	**3.19**
Developed Agricultural Land, Grass, and Meadow	**5.39**	**0.00**
Other	**2.19**	**0.28**

Fire and Logging

Fire is recognized as the principal natural disturbance initiating stands in the boreal forest (Johnson 1992). Therefore, since logging in the GCF didn't start until 1923, all stands in the FRI with ages indicating a year of origin prior to 1923 were assumed to have originated from fire. Stands with origin dates since 1923 were assumed to have originated from logging with the exception of those areas recorded in the Ontario Forest Fire History Atlas as having burned. This could give a small overestimate of the area logged since the Atlas only includes fires >300 ha and smaller fires may have burned over previously logged areas. However, for the period 1976-1995, we also had available nonspatial data on all recorded fires which gave the start location coordinates. By overlaying these fire data points onto the age cover and matching the fire dates with the stand ages, we were able to detect smaller areas that burned since 1976.

While dates of known fires obtained from the Fire History Atlas are assumed to be accurate to the year, all other stand ages were obtained from air photo interpretation and measurement of sample plots with a sampling intensity of approximately one per 2.6 km^2 (Ontario Ministry of Natural Resources 1986). The ages obtained from coring canopy trees at the presumed transition from root to shoot have been found to underestimate the actual ages due to the early prostrate growth of some species such as balsam fir and the development of adventitious roots above the true root crown in most boreal tree species (DesRochers and Gagnon 1997; Parent et al. 2000, 2002; Gutsell and Johnson 2002). This underestimation is greater for slow growing species such as black spruce and balsam fir than for faster growing species such as jack pine and aspen. Thus, most stand ages may only be accurate to "5-10 years and most analyses were done on grouped data using 10 year age classes.

Using the above procedures, we could date 96% of the total productive area of the GCF to its most recent stand-origin disturbance by either fire or logging, producing a time-since-last-disturbance map. Henceforth, 'total productive area' refers to the total productive area that could be aged. From these data, the time-since-disturbance distribution (using 10 year age classes) was determined by plotting the cumulative proportional area by age class as described by Johnson and Gutsell (1994) and Reed (2001). A straight line plot on semi-log paper would indicate a cumulative negative exponential distribution with the slope giving the disturbance cycle (the time required to disturb an area equal in size to the whole study area) (Johnson and Van Wagner 1985). The area under the curve to the right of any point along the bottom axis would represent the area older than that age. The longer the disturbance cycle, the gentler the slope and the greater the area of older aged forests. Statistically significant breaks in the distribution with changes in slope would indicate a mixed distribution with periods (epochs) of different disturbance cycles (Johnson and Gutsell 1994). An epoch is defined as a period of constant disturbance cycle. Using the method given by Reed et al. (1998) and Reed (2001), we calculated maximum likelihood estimates (MLE) of the disturbance cycle and 95% confidence limits around these estimates for each epoch. The change points defining each epoch were selected from the changes in slope of the time-since-disturbance distribution.

In order to understand and explain the shape of this distribution, we looked individually at the effects of fire and logging on the forest age distribution. To determine what the fire frequency distribution would be in the absence of logging, we needed to know the date of fire origin of the stands that were logged. We estimated these fire origin dates by assuming: a) that logging has not influenced the area burned by wildfires; and b) that only stands older than the calculated rotation would have been logged. The rotations differ by stand type, ranging from 55-65 years for *Populus tremuloides* and 45-70 years for *Pinus banksiana* to 75-100 years for *Picea* spp (Ontario Ministry of Natural Resources 1986). Due to the dominance of *Picea* in the GCF and the abundance of stands greater than the maximum of these rotations, we assumed that most stands that were logged would have been 90-120 years old. Therefore, by allocating the area logged in each decade equally between the 4 decades 90-120 years earlier, we obtained our estimated time-since-fire distribution in the absence of logging. Of course, logged areas that subsequently burned would already have fire-origin dates as their year of origin and would not have been attributed to logging as the cause of origin. Using this estimated time-since-fire distribution, we calculated maximum likelihood estimates (MLE) of the fire cycle (and 95% confidence intervals around these estimates) for each epoch, again using obvious changes in slope of the time-since-fire distribution to determine the change points.

To determine the effect of logging alone on the forest age distribution, we first determined the changes in logging rates over time by examining the area harvested by year. Recall that our estimates of area per year were obtained from the areas covered by each stand origin year after 1922 minus the areas known to have burned (from the fire records). Where the fire records are incomplete (e.g. for small fires prior to 1976), we would be overestimating the area harvested. However, where fires burned over harvested areas, we would be underestimating the area harvested. Given that both of these probably account for a small proportion of the total area harvested and since they have counteracting effects, it may be reasonable to assume that their overall effects may approximately balance each other. Since, unlike fires, logging occurred every year with much less year-to-year fluctuation and no areas were logged twice, the rate of area logged since 1923 could be used to estimate the actual disturbance cycle due to logging.

Settlement and Logging

For the second objective of comparing the landscape patterns resulting from logging in the GCF and settlement in the corridor, we investigated both spatial and temporal aspects of the landscape mosaic by analyzing the sizes and shapes of polygons defined as areas of uniform land use code and year of origin. For the GCF, we used only those polygons that were designated as having originated from logging by the criteria explained previously. For the corridor, we used only those polygons classified with a land use code of productive forest and those classified as 'developed agricultural land' and 'grass and meadow'; these two latter categories were combined and hereafter referred to as simply agriculture. In 1996, 81% of the total area of the corridor was classified as productive forest. These areas would have been settled and either logged without subsequent conversion to agriculture or cleared for agriculture, abandoned, and subsequently regenerated as forest. Therefore, in order to investigate impacts of these different land uses on the spatial mosaic of the study area, we compared the sizes and shapes of polygons among three categories of polygons: agriculture in the corridor, productive forest in the corridor, and productive forest that originated from logging in the GCF. All percentages were calculated from the total areas for each of these three polygon categories.

We used both percentage size distributions and Lorenz curves to evaluate the proportional distribution of area among polygon size classes for each of the three categories. Lorenz curves (Lorenz 1905; Kotz and Johnson 1985) are used in economics to depict the distribution of wealth among the population. Here they were used to depict the distribution of area among polygon size classes. A straight diagonal line would represent the situation in which the total area is divided equally among all size classes; the greater the divergence from the diagonal, the greater the inequality in distribution. Polygon shapes in these three land use categories were compared using perimeter to area (P/A) ratios; the greater the ratio, the more complex the shape. We could have used several other measures of shape but most give results correlated to P/A ratios. Mean P/A ratios were calculated for polygons grouped by polygon size.

Finally, we looked at temporal trends in the spatial age mosaic to get a better understanding of the influence of settlement and logging on the forest landscape. We used data from the current (i.e. 1996) productive forest in the corridor and from the productive forest in the GCF that originated from logging. We compared first the age distributions resulting from these two land uses and then the polygon sizes and shapes (P/A ratio) by year of origin grouped into 10 year age classes.

RESULTS AND DISCUSSION

Effects of fire and logging on the landscape age distribution

Results for the first objective are presented by first examining the combined effects of these two disturbances on the disturbance cycle and then determining what the disturbance cycles would be from each of these two disturbances separately.

Disturbance by fire and logging combined

Despite continuous logging for almost 80 years, the forest is not yet in regulation. However, as indicated in Figure 5, the five youngest age classes do show some indication of a more uniform age distribution. Prior to the 1930s, there is more extreme variation in areas assigned to each decade of origin. The extremely large areas originating in the 1850s and 1890s are attributable largely to a single year in each of these decades. The origin year of 1850 currently accounts for 391,847 ha (27.4% of the total productive area) while the year 1895 accounts for 137,587 ha (9.6%). The original areas burned in these years would have been even larger since the areas indicated here are remnants of these burns that have escaped subsequent disturbances by fire or logging. In the 20th century, the year with the largest area originating from fire (63,072 ha or 4.4% of the total productive area) is 1923 which was also the year that logging began in the GCF. After 1923, there is less interdecadal variation. At the yearly scale, areas range from a low of 102 ha originating in 1926 to a high of 22,707 ha originating in 1989.

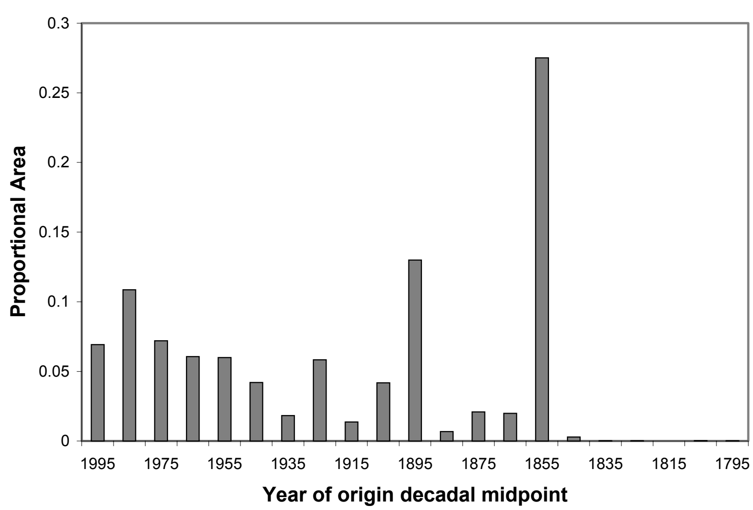

Figure 5. Age class distribution in 1996 of the productive area of the Gordon Cosens Forest showing the proportion in each year of origin (1797-1996) grouped by decades which are labeled by decadal midpoint (e.g. 1995 for 1990-1999). Note that the first and last classes do not span a full decade.

Figure 6 shows just the post-1923 age distribution of the GCF by year of origin. It is clear that most of the disturbances after 1923 are attributable to logging. For the polygons originating after 1923, only 5% of the area originated from fire while 95% originated from logging.

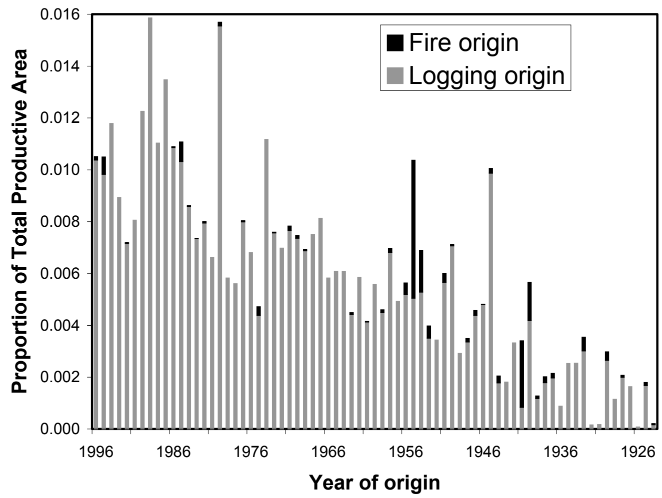

Figure 6. Proportion of the total productive area in 1996 of the Gordon Cosens Forest attributed to each year of origin for the period 1924-1996.

The time-since-disturbance distribution (Figure 7) shows an obvious change in slope around 1860. Before 1860 the estimated disturbance cycle was 32 years with 95% confidence limits of 29 to 35 years while after 1860 the estimated disturbance cycle was 250 years with 95% confidence limits of 235 to 266 years. Interestingly, there is no obvious break and significant decrease in the disturbance cycle associated with the start of logging in 1923 although, as will be shown later, logging has had an impact on the disturbance cycle.

The large gap in the time-since-disturbance distribution (Figure 7) in the mid 1800s is due to the extremely large area that burned in 1850. From both the large area still remaining from this burn (Figure 5) and the widespread spatial distribution of polygons with an 1850 year of origin representing the remnants of this burn (now separated by areas that have subsequently been disturbed by fire, logging, or settlement), it would appear that a very large part of the GCF and corridor burned in 1850. As pointed out by Johnson and Gutsell (1994), the occurrence of a single disturbance that covers approximately one-third or more of the study area means that the study area is not large enough relative to the size of disturbance to produce a reliable estimate of the disturbance cycle, resulting in deviations around the estimate.

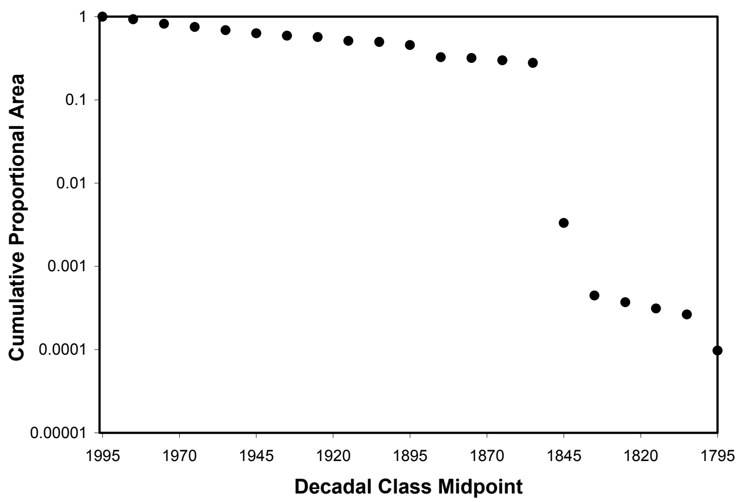

Figure 7. Time-since-disturbance distribution for the total productive forest area of the Gordon Cosens Forest spanning the years 1797-1996.

Disturbance by fire

We obtained the time-since-*fire* distribution for the GCF (Figure 8) by considering the scenario in which no logging had occurred and all logged stands are dated to their year of origin from fire by assuming logged stands were 90-120 years old when logged. This distribution shows two changes in slope, the first at 1850 and the second at 1900. The maximum likelihood estimates of the fire cycle (with 95% confidence intervals) is 32 (26 – 39) for the first epoch prior to 1850, 82 (76 – 88) years for the second epoch 1850-1899, and 1,598 (1,356 – 1,901) years for the post 1900 period. Thus, the fire cycle appears to have increased somewhat midway through the 19th century and then increased by orders of magnitude at the start of the 20th century. The change to a longer fire cycle around 1890-1900 is consistent with the findings of other fire frequency studies across the boreal forest (Johnson 1979; Yarie 1981; Suffling et al. 1982; Bergeron and Archambault 1993; Larsen 1997; Weir et al. 2000) and has been attributed to climatic change at the end of the Little Ice Age (Bergeron and Archambault 1993). The change found here in the mid 1800s has not been found in other studies and is largely a result of the single large fire that occurred in 1850 as explained above.

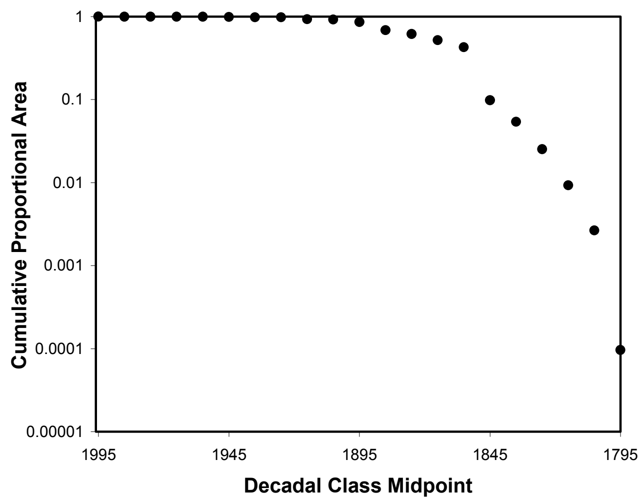

Figure 8. Time-since-fire distribution for the Gordon Cosens Forest estimated under the assumptions that logging does not influence fire and that areas logged ranged in age from 90-120 years at the time of logging.

A comparison of the time-since-fire distribution with the time-since disturbance (including both fire and logging) distribution (Figure 9) clearly shows the effect of logging in increasing the disturbance rate (slope of the line) for the post 1923 period and decreasing the proportional area of older-aged forests.

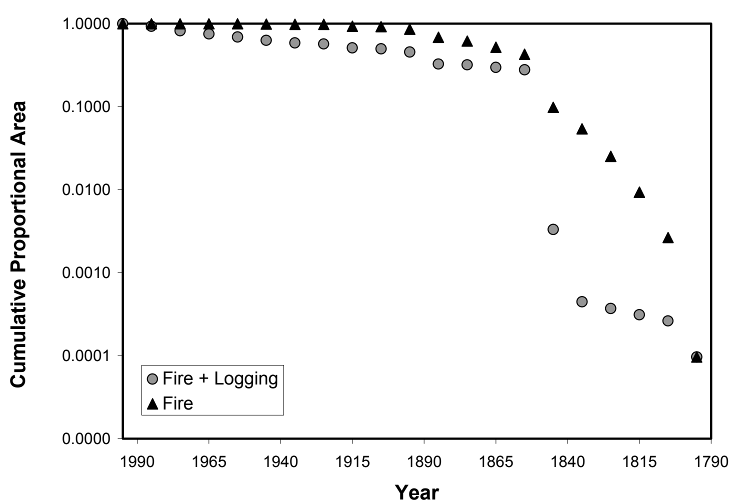

Figure 9. Comparison of the time-since-disturbance (logging plus fire) distribution indicated by gray circles and the time-since-fire distribution indicated by black triangles.

As discussed earlier and shown in Figure 6, most of the disturbance in the past 80 years has been due to logging. However, this should not be taken as an indication that fire is no longer significant in determining the disturbance cycle. While the GCF has not had any large fires since 1923, adjacent areas to the west, south and southeast have had large fires since then as shown by Figure 10. The large fires indicated on the map in the southern part of the GCF occurred in 1923. The large fires that occurred outside the GCF (Figure 10) occurred in 1936, 1941, 1948, 1955, 1961 and 1995. The lack of large fires after 1923 in the GCF cannot be attributed either to logging or to fire suppression since both activities have also been occurring in neighbouring areas that did experience large fires in this period. Thus, such fires cannot be ruled out for the GCF at some future time.

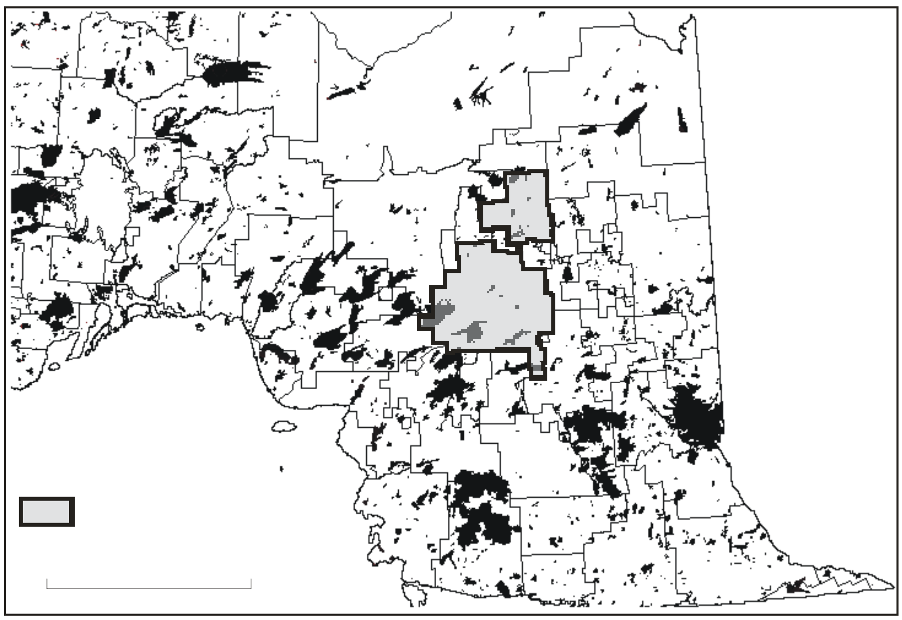

Figure 10. Map of all fires >300 ha (black areas) in and around the Gordon Cosens Forest for the period 1921-1995, obtained from Ontario's Forest Fire History Atlas (Ontario Ministry of Natural Resources 1998).

Disturbance by logging

The total area logged in the GCF from 1923-1996 is estimated at 605,845 ha (42.3% of the total area of productive forest). Note that this estimate is based on the areas attributed to logging origin as of 1996 and therefore assumes that none of the logged areas had subsequently burned. We have no way to identify any areas that had been logged and subsequently burned; such areas are identified as fire origin polygons and therefore are not included in this total of logged area. Figure 11 gives the mean area logged per year for each decade from 1923 to 1996. This graph indicates a relatively steady increase in the rate of harvesting although there was a slight decline in the 1990s due to a long period of uncertainty following the announcement by the Kimberly-Clark Corporation in June 1990 that it was selling the Spruce Falls Power and Paper Company.

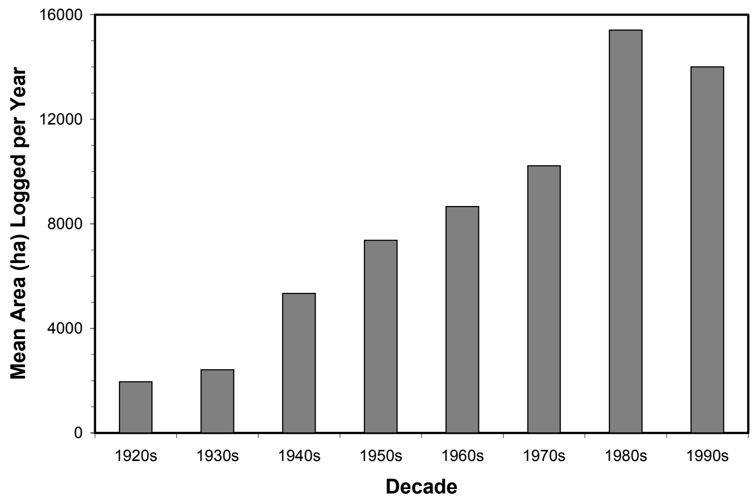

Figure 11. Mean area logged per year for each decade for the period 1923 to 1996, assuming that none of the logged areas had subsequently burned.

The rate of harvesting of the most recent 10 years of record (1987-1996) is 15,580 ha per year which is 1% of the productive forest (i.e. a rotation of 100 years). However, the average harvest per year for the entire duration of commercial forestry in the GCF (1923-1996) is only 8,187 ha per year or 0.5% of the productive forest, representing a rotation of 200 years. Thus, as indicated by the empirical cumulative age distribution of the GCF given in Figure 7, there is still a significant proportion (45.6%) of the productive forest in the GCF that is beyond a rotation age of 100 years. Even at a harvest rate of 1% of the productive forest, it would take more than 50 years just to log those areas that have not yet been logged. In that time, it is highly likely that fires will occur. Unlike logging, fires occur in stands of all ages as indicated by the negative exponential time-since-disturbance graphs. Thus, it is unlikely that the age distribution of the GCF will resemble that of a regulated forest.

Comparing the effects of settlement and logging on the landscape mosaic

Results for the second objective are presented by first comparing the spatial mosaic pattern of the settlement corridor with that of the logged productive forest of the GCF and then examining temporal changes in the landscape mosaic of the productive forest in both the corridor and the GCF.

Figure 12 provides a general overview of the spatial mosaic pattern of the two land uses of settlement and commercial forestry, showing the obviously finer scale mosaic pattern of the settlement corridor compared with the coarser scale pattern of the GCF. Note that productive forest originating prior to settlement was grouped into the category "1797-1912" and polygons classified as agriculture are grouped into a single category since data for their year of origin are not included in the FRI data base. The category "0" contains productive forest for which the year of origin was unknown. The "other" category includes open and treed muskeg, rock, etc.

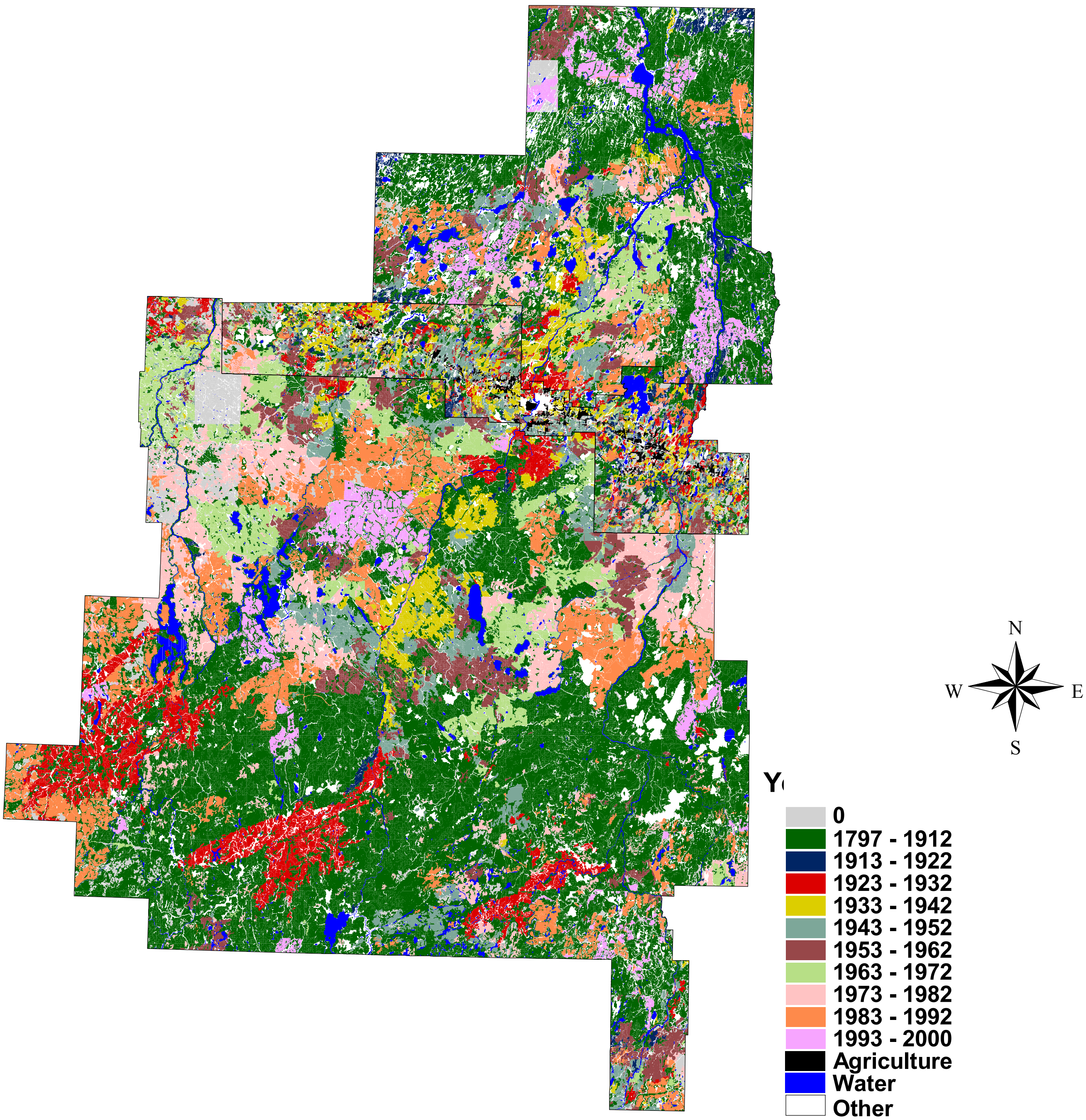

Figure 12. Spatial age mosaic of the Gordon Cosens Forest and the settlement corridor.

Spatial patterns

The spatial patterns indicated in Figure 12 were further investigated by comparing both the sizes and shapes of the polygons in the GCF versus the settlement corridor. Size distributions were examined first with a polygon size class distribution (using 50 ha size classes) and second with Lorenz curves. For these analyses, polygons in the corridor area were further subdivided by land use designated as agriculture or productive forest. As indicated in Figure 13, half of the agriculture area of the corridor consists of polygons <50 ha with a rapid decline in the proportion of area consisting of larger polygons. In contrast, the area of the GCF is more evenly distributed among all size classes with 20% of the GCF consisting of polygons >800 ha. The polygon size distribution for the productive forest in the corridor is very similar to that for the agriculture category, indicating the dominant influence of settlement pattern on the productive forest in the corridor. Of course, the smaller total area of the corridor compared to the GCF would also limit to some extent the number of large polygons that can exist in the corridor productive forest.

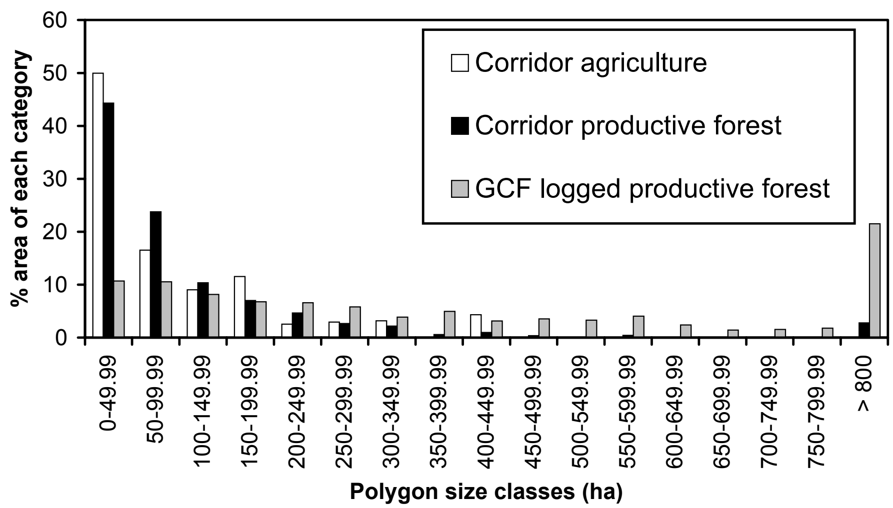

Figure 13. Percent distribution of area among polygon sizes (in 50 ha classes) for the land uses of agriculture and productive forest in the settlement corridor and logged productive forest in the Gordon Cosens Forest (GCF).

The Lorenz curves (Figure 14) further illustrate the inequitable distribution of area among polygon size classes for all three categories. The logged area of the GCF contains the most disproportionate amount of area in large polygons (as indicated by the greatest divergence from the diagonal), again indicating the tendency to log relatively large patches. Somewhat counterintuitively, a greater proportion of the agriculture area in the corridor is contained in larger polygons compared with the productive forest area in the corridor. However, this result is an artifact of our definition of polygons for agriculture areas versus productive forest. Polygons for productive forest were defined by year of origin but since polygons for agriculture do not have a year of origin, adjacent farms that may have been settled at different times could not be distinguished as separate polygons. On the other hand, former adjacent farms that had been abandoned and become reforested in different years could be distinguished as separate polygons.

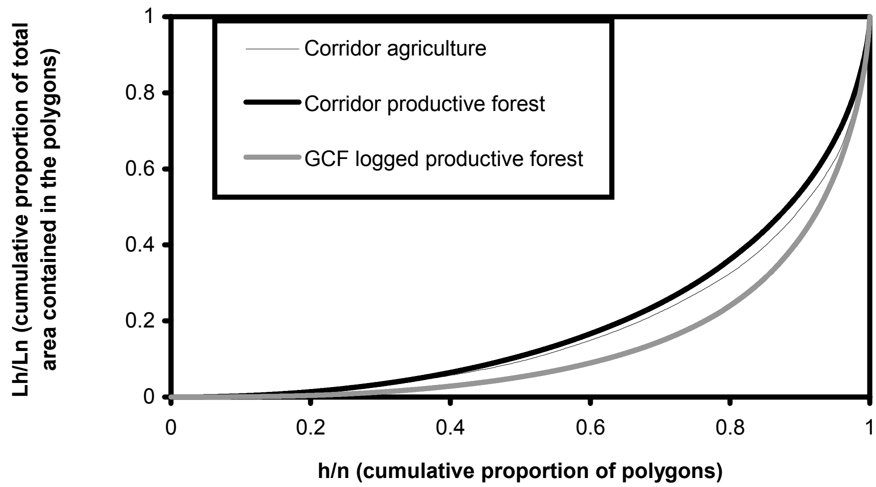

Figure 14. Lorenz curves illustrating the inequitable distribution of area among polygon size classes for areas classified as agriculture and productive forest in the settlement corridor and productive forest in the Gordon Cosens Forest (GCF) originating from logging.

Polygon sizes in the corridor are controlled by homestead requirements. Homesteads away from the railway were 64.7 ha in size prior to 1925, and those near the railway were 40.5 ha in size (Algoma Central 1913; McDermott 1961). This was reduced to 32.4 ha in 1925 to discourage those who claimed homesteads only to clear and sell the wood without establishing farming operations. The minimum area that had to be cleared annually by settlers according to settlement agreements was 0.8 ha (McDermott 1961). Thus, it is not surprising that approximately half of the corridor area is comprised of polygons < 50 ha in size (Figure 13).

Polygon sizes in the logged portion of the GCF are determined by the harvest method – in the boreal forest this is primarily clearcutting (Johnson et al. 1995). Given a homogeneous stand of trees, it is more economical for a forestry company to clear large patches, due to increased efficiency in transporting the crew, machinery, and timber between the clearing site and the processing centre. Large, open clearcuts also provide the exposed forest soil and light necessary for the establishment and growth of most boreal forest tree species (Chrosciewicz 1974; 1976; Zasada et al. 1983; Thomas and Wein 1985; Weber et al. 1987; Greene et al. 1999; Charron and Greene 2002; Greene et al. 1999). In addition, tree planting programs reduce the need to preserve a certain distance from the forest edge or to retain leftover patches as seed sources for natural seeding (Greene and Johnson 2000; Greene et al. 2002).

Polygon shapes as described by perimeter to area (P/A) ratios are also influenced by land use type. For the smallest polygon size class of <50 ha (Figure 15), the significantly lower P/A values for corridor agriculture are due to the simple polygon shapes resulting from the grid survey system. This system, commonly employed in North America, partitions the landscape into square- or rectangle-shaped homesteads that are then distributed to settlers. No effort was taken in the study area to exclude terrain unsuitable for agriculture (Troughton 1983); this meant that everyone received and was supposed to clear a regular-shaped piece of land. The P/A ratios for the smallest polygon size class of the two productive forest categories are significantly higher than those of agriculture but are not significantly different from each other. The high P/A ratios for the small polygon sizes in the corridor productive forest can be explained by small irregular-shaped fires and forest growth on abandoned roads while in the logged productive forest of the GCF they might be explained by harvesting of thin strips along rivers that occurred early on when rivers were the main method of transporting logs.

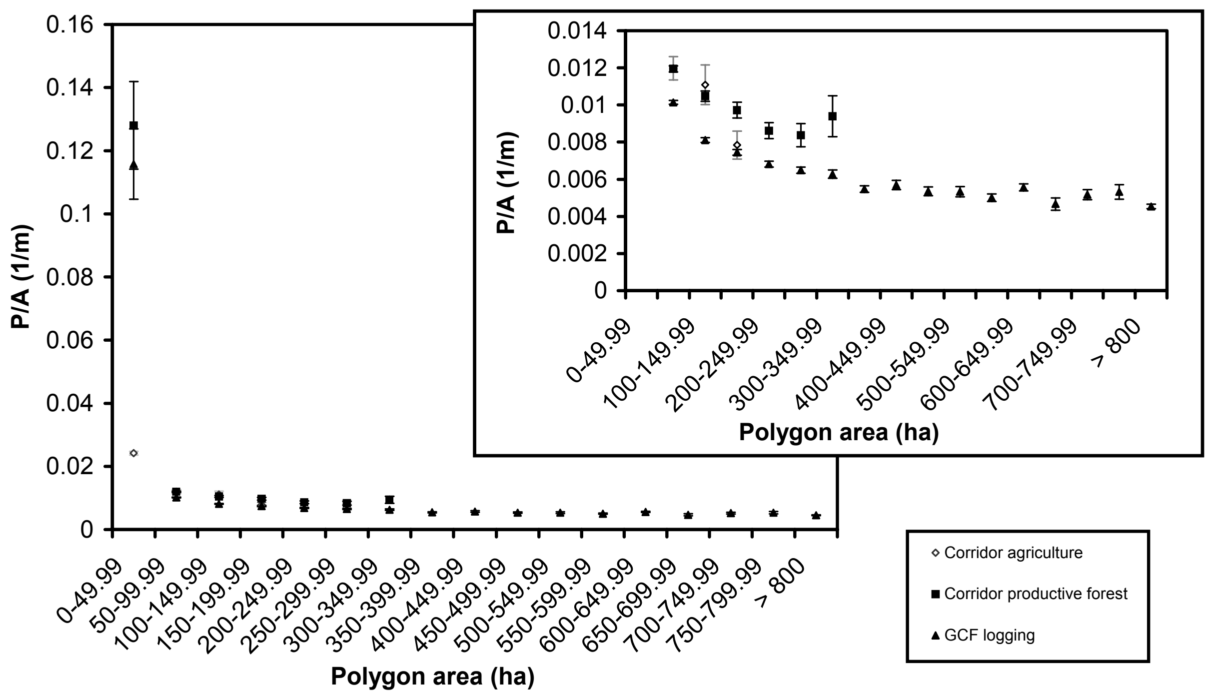

Figure 15. Mean (± SE) perimeter-to-area (P/A) ratios of polygons by polygon size class for agriculture and productive forest in the settlement corridor and logged productive forest in the Gordon Cosens Forest (GCF). The inset graph has a different scale on the y-axis to show more clearly the data for size classes >50 ha. The lack of data for the corridor beyond 300 ha is due to the very small numbers of polygons in the larger size classes.

The general trend of decreasing P/A ratio with increasing size (area) of polygons indicated in Figure 15 is to be expected since for the simple circular shape, $P/A = 2\pi r/\pi r^2 = 2/r$ (i.e. as radius increases, P/A ratio decreases). Thus, of real interest here is the significant differences in P/A ratios between the corridor productive forest and the GCF logged productive forest for polygons >50 ha in size (Figure 15 inset). The low P/A values for the GCF reflect the simpler shapes of clearcuts while the higher P/A values for the corridor productive forest reflect the more complex patterns of land clearance and subsequent abandonment at different times by settlers. It should also be noted that the data for the corridor productive forest included fire origin polygons since polygons could not be distinguished by their cause of origin. Therefore, the irregular shapes of fires would also contribute to higher P/A values for the corridor productive forest.

Temporal patterns

In this section we were interested in discerning any differences between the two land uses of settlement and commercial forestry in the spatial mosaic pattern over time (i.e. any differences in polygon sizes and shapes by year of origin). These temporal patterns would lead to a better understanding of the development of the current landscape mosaic. For these analyses, we only used the productive forest portion of the settlement corridor since the agriculture areas could not be dated to year of origin. Recall from Table 1 that 81% of the settlement corridor was classified in 1996 as productive forest and therefore captures most of the corridor area.

First, we compared the age distributions for the productive forest in the corridor and the logged productive forest of the GCF. Many of the productive forest polygons in the corridor originated between 1913-1952 (Figure 16), which corresponds to land clearing and abandonment. According to McDermott (1961), about 81% of farms were abandoned "south of Kapuskasing" and 91% "east of Hearst" between 1931 and 1961. Reforestation declined since 1952 due to decline in settlement in the region, which reduced the rate of clearing and abandonment of land. However, as noted earlier in Figure 11 and also shown here in Figure 16, logging in the GCF has been steadily increasing since 1923, reflecting increasing demand as well as technological advances such as the replacement of horses with wheeled skidders and introduction of power saws. The decrease in the 1990s is due partly to the shorter period of time included in that year of origin class and partly to an actual decline in harvest related to the company's economic uncertainties during that decade.

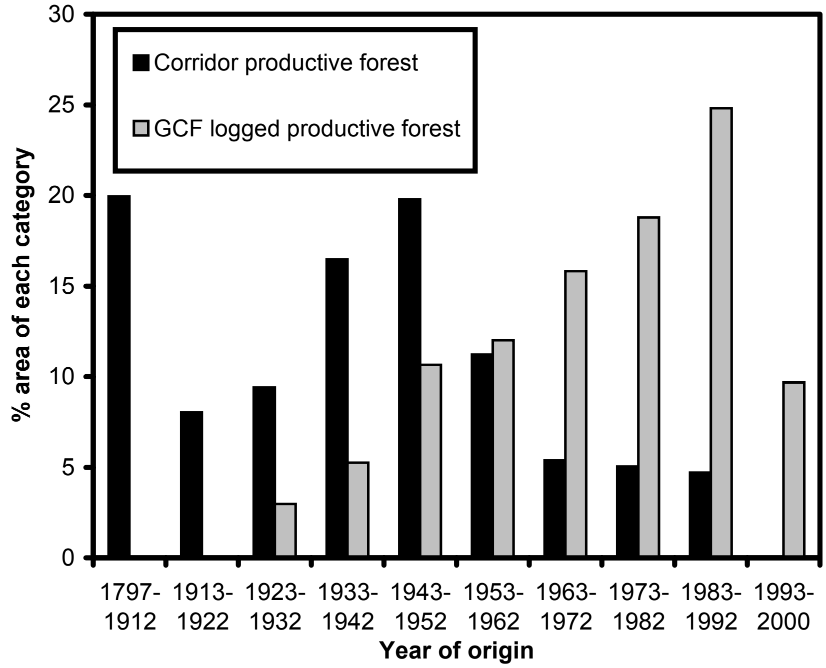

Figure 16. Distribution of area by year of origin for the productive forest in the settlement corridor and the Gordon Cosens Forest (GCF). Note that the first category contains all polygons originating prior to human settlement.

As shown in Figure 17, polygon sizes of the GCF logged productive forest areas are significantly larger those of the corridor productive forest for all years of origin. The larger polygons of the GCF originate from clearcuts approximately 80-120 ha in size while the smaller 20-40 ha polygons of the corridor productive forest originate either from farm abandonment or fire. The upward trend in polygon size in the corridor productive forest most likely reflect the fact that polygons of more recent origin (either by fire or by farm abandonment) reflect the actual size of the forest stand originating by either cause. On the other hand, older stands are more likely to have been subsequently disturbed (e.g. by fire) and thus their current polygon sizes are the remnants of earlier established forests from farm abandonment and fires. Similarly, fires occurring in the 1940s and 1950s in the GCF (Figure 6) could have reduced the sizes of some remnants of earlier cuts, also resulting in the observed general trend of increasing polygon size with time. However, this would not wholly explain the significant increase in mean polygon size in the 1960s; this increase corresponds with the shift from the use of horses to wheeled skidders in logging operations which may be a better explanation. With increased mechanization, there has been an increase both in total area logged (Figure 16) and in mean size of clearcuts (Figure 17). However, maximum clearcut size is also regulated by the government and such regulations change over time; any such changes would be reflected in the landscape mosaic.

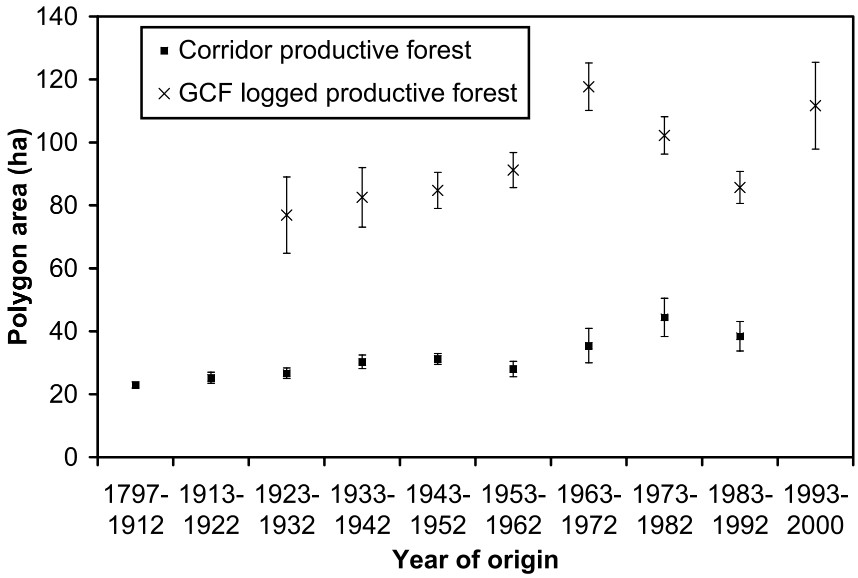

Figure 17. Mean (± SE) size of polygons (ha) by year of origin grouped into 10 year age classes for the productive forest in the settlement corridor and the logged productive forest in the Gordon Cosens Forest (GCF). Note that all polygons originating prior to 1913 are grouped into the first category.

We also looked at differences between the corridor and GCF in polygon shape (i.e. P/A ratio) over time. Figure 18 shows that polygons in the corridor productive forest have high P/A ratios, except for the years 1913-1922 and 1933-1942 that contain simpler shapes due to farm abandonment. Although abandonment was also occurring in 1923-1932, P/A ratios for these years are high. This may possibly be due to the effect of fire, as 1923 was a large fire year in the region. Fire generally produces more complex shapes due to their convoluted perimeters. For the years since 1942, P/A ratios are intermediate. Land abandonment and reforestation were at a decline, particularly after the 1950s, and small fires were also occurring. The decade 1983-1992 shows an extremely high P/A with large SE due primarily to a single 67 ha polygon with a P/A of 14. Excluding that polygon brings the P/A value down to 0.23 (+/- 0.08). That is still higher than the preceding decades; however, very little abandonment was occurring in the late 20th century, and most of these polygons likely originated from fire.

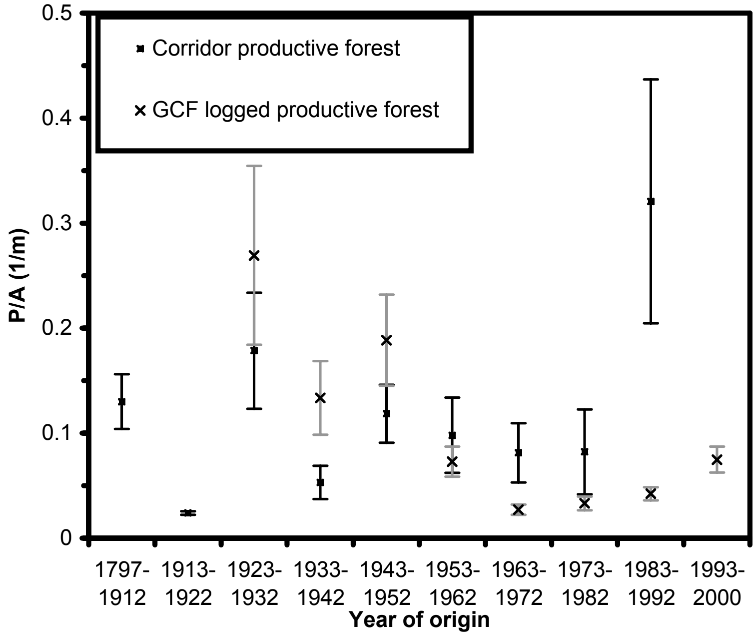

Figure 18. Mean perimeter-to-area ratios (± SE) of polygons by year of origin (grouped in 10 year classes) for productive forest in the settlement corridor and logged productive forest in the Gordon Cosens Forest (GCF). Note that the first category contains all polygons originating prior to human settlement.

The P/A ratios for the GCF productive forest generally decrease with time (Figure 18), suggesting that polygon shapes have been getting simpler. This would be partially explained by the larger areas of clearcuts as indicated in Figure 17; as discussed earlier, with no change in shape, P/A ratios decrease with increasing area. The decrease in P/A ratio may also be partially due to less time for clearcuts to become more complex in shape due to natural disturbances occurring within or extending into a clearcut. The period 1923-1932 shows the highest P/A, since early logging was conducted in smaller patches, mainly along rivers. Logging in subsequent decades (1933-1942 and 1942-1952) was also largely limited to areas adjacent to rivers, and the resultant forest patches also have relatively high P/A values. As mentioned previously, increasing mechanization of the forestry process allowed for logging away from rivers and in larger blocks. This phenomenon is reflected in the reduction of P/A after 1952.

CONCLUSIONS

We can draw several conclusions from the first part of the study which examined the landscape age distributions resulting from disturbance by fire and logging. First, despite logging for almost the time span of a rotation of 100 years, the age distribution of the GCF still resembles more that of an area subject to natural disturbance by fire than that of a regulated forest. However, this appears to be due largely to the fact that, for most of the GCF's logging history, harvesting rates have been well below that for a rotation of 100 years. Only in the last 10 years of data ending in 1996 has the annual area logged approached that for a sustained rotation of 100 years. The second conclusion is that the disturbance cycle of the GCF has increased significantly since the 19th century, whether we consider only fires or both fires and logging combined. Similar areas in the southern boreal forest of Quebec have also shown an increase in fire cycle coincident with the end of the Little Ice Age (Bergeron and Archambault 1993). Furthermore, studies across the North American boreal forest have found a similar increase in fire cycle at the end of the 19th century (Johnson 1979, Yarie 1981, Suffling et al. 1982, Bergeron 1991). The third conclusion concerns the assumption that logging has replaced fire as the stand originating disturbance. While Figure 6 (which shows the annual area originating from fire and logging) appears to support this assumption, the map of fires >300 ha for the period 1920-1995 (Figure 10) indicates that wildfires have not been eliminated or reduced to an insignificant role in this region. In fact, what Figure 10 does point out is the importance of scale and size of study area on estimates of the fire cycle. As pointed out by Bridge (2001), adjacent study areas can have very different estimated fire cycles, depending on the locations of recent large fires. Furthermore, the wide confidence intervals of 97 to 1249 years around the current estimated disturbance (logging plus fire) cycle for the GCF suggests caution in interpreting the estimate of 188 years. As shown by Weir et al. (2000), the occurrence of a single large fire can significantly alter the estimate for the current fire cycle. Thus, any move to use forestry practices to emulate natural disturbance by fire must take into consideration that the landscape pattern is a product of both fire and logging. Since these two disturbances differ in that logging only disturbs forests beyond the rotation age while fire burns through stands of all ages, it is unlikely that the GCF will ever resemble the regulated forest depicted in Figure 1a.

Besides the logging of commercial forestry, this study shows clearly the impacts of agricultural settlement in the southern boreal forest. These two human disturbances of logging and settlement produce very different patterns on the boreal forest landscape (Figure 10). A previous study by Weir et al. (2000) showed the influence of such settlement on the fire frequency of adjacent unsettled forest not subjected to logging. However, in this study we showed that agricultural settlement and commercial forestry result in distinct mosaics that differ in both polygon size and shape. The settlement landscape has a finer scale mosaic pattern (i.e. smaller polygons) due to the effect of the grid survey system and homestead requirements that limited the sizes of homesteads. Most of the productive forest currently found in the settlement landscape of the southern boreal forest established on land that had been cleared for agriculture and subsequently abandoned in the first half of the 20th century. Although settlement and farm abandonment occurred fairly early in the 20th century in this part of the boreal forest, the spatial age mosaic of this forest will continue for some time to reflect the pattern of settlement and farm abandonment with not only smaller polygons but also polygons of more complex shapes compared with the pattern produced by commercial forestry. The latter land use produces a spatial age mosaic consisting of large polygons with simpler shapes (less convoluted perimeters) due to the clearcut harvesting procedure. Thus, despite the fact that the boreal forest regenerates (for the most part through natural seed dispersal and seedling establishment) following both types of disturbance/land uses, the resulting landscapes show significant differences.

A previous study by Weir et al. (2000) showed that the spatial age mosaic produced by wildfires consists of a mix of large younger aged polygons of more complex shape and small older polygons (the remnants of previous large fires that have been largely overburned) of simpler shapes. On the other hand, commercial forestry in the boreal forest tends to produce typically large polygons of simple shape while settlement tends to produce small polygons of more complex shape. Neither resembles the landscape pattern produced by fire. In terms of emulating natural disturbance through forestry practices, it may be possible to vary the sizes of clearcuts or to increase the complexity of the shapes of clearcuts. However, there are two limitations to such practices emulating natural disturbance. The first is that the temporal pattern of polygons decreasing in size and complexity that occurs due to the overburning by wildfires of previously burned areas would not be emulated by forestry practices. Unlike fires that burn stands of all ages, logging would only occur in stands beyond the rotation age. The second limitation is that, as discussed earlier, fire is still burning large areas of the North American boreal forest (Stocks 1991) and is therefore still playing an important role in influencing the spatial age mosaic. Thus the landscape pattern of the boreal forest, even in areas under forest management since 1923, reflects (and is likely to continue to reflect) the effects of both natural and human disturbances.

LITERATURE CITED

Algoma Central. 1913. The Great Clay Belt of Northern Ontario. Temiskaming and Northern Ontario Railway Commission.

Allen, O. W. 1889. The land prospectors manual and field book for the use of intending settlers taking up lands in Manitoba and the Northwest Territories of Canada. Department of the Interior, Government Printing Bureau, Ottawa, Canada.

Beattie, K. G., W. K. Bond, E. W. Manning. 1981. The agricultural use of marginal lands: a review and bibliography. Lands Directorate, Environment Canada. Working Paper No. 13.

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

Bergeron, Y., and S. Archambault. 1993. Decreasing frequency of forest fires in the southern boreal zone of Québec and its relation to global warming since the end of the 'Little Ice Age.' Holocene 5: 255-259.

Bergeron, Y., B. Harvey, A. Leduc, and S. Gauthier. 1999. Forest management guidelines based on natural disturbance dynamics: stand- and forest-level considerations. For. Chron. 75: 49-54.

Bridge, S. R. J. 2001. Spatial and temporal variations in the fire cycle across Ontario. Ont. Min. Nat. Res., NEST Tech. Rep. TR-043.

Canada Department of Agriculture. 1972. Soils of Canada map. Cartography Section, Soil Research Institute, Canada Department of Agriculture, Ottawa, ON.

Carleton, T. J., and P. MacLellan. 1994. Woody vegetation responses to fire versus clearcutting logging: a comparative survey in the central Canadian boreal forest. Ecoscience 1(2): 141-152.

Charron, I., and D. F. Greene. 2002. Post-wildfire seedbeds and tree establishment in the southern mixedwoodboreal forest. Can. J. For. Res. 32: 1607-1615.

Chrosciewicz, Z. 1974. Evaluation of fire-produced seedbeds for jack pine regeneration in central Ontario. Can. J. For. Res. 4: 455-457.

Chrosciewicz, Z. 1976. Burning for black spruce regeneration on a lowland cutover site in southeastern Manitoba. Can. J. For. Res. 6: 179-186.

Clayton, J. S., W. A. Ehrlich, D. B. Cann, J. H. Day, and I. B. Marshall. 1977. Soils of Canada. Research Branch, Canada Department of Agriculture, Supply and Services Canada, Ottawa, ON.

Desrochers, A., and R. Gagnon. 1996. Is ring count at ground level a good estimation of black spruce age? Can. J. For. Res. 27: 1263-1267.

Drapeau, P., A. Leduc, J.-F. Giroux, J.-P. L. Savard, Y. Bergeron, and W. L. Vickery. 2000. Landscape-scale disturbances and changes in bird communities of boreal mixed-wood forests. Ecol. Monogr. 70(3): 423-444.

Environment Canada. 2002. Canadian climate normals: Kapuskasing a. url: http://www.msc.ec.gc.ca/climate

Ericsson, S., L. Östlund, and A.-L. Axelsson. 2000. A forest of grazing and logging: deforestation and reforestation history of a boreal landscape in central Sweden. New Forest. 19: 227-240.

Fitzgerald, D. F. 1965. Pioneer settlement in northern Saskatchewan. Dissertation, University of Minnesota, Minneapolis, Minnesota, USA.

Gluck, M. J., and R. S. Rempel. 1996. Structural characteristics of post-wildfire and clearcut landscapes. Environ. Monit. Assess. 39: 435-450.

Greene, D. F., and E. A. Johnson. 2000. Tree recruitment from burn edges. Can. J. For. Res. 30: 1264-1274.

Greene, D. F., D. Kneeshaw, C. Messier, V. Lieffers, D. Cormier, R. Doucet, K. D. Coates, A. Groot, G. Grover, and C. Calogeropoulos. 2002. Modelling silvicultural alternatives for conifer regeneration in boreal mixedwood stands (aspen/white spruce/balsam fir). For. Chron. 78: 281-295.

Greene, D. F., J. C. Zasada, L. Sirois, D. Kneeshaw, H. Morin, I. Charron, and M. J. Simard. 1999. A review of the regeneration dynamics of North American boreal forest tree species. Can. J. For. Res. 29: 824-839.

Gutsell, S. L. and E. A. Johnson. 2002. Accurately aging trees and examining their height growth rates: implications for interpreting forest dynamics. J. Ecol., in press.

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

Ihse, M. 1995. Swedish agricultural landscapes – patterns and changes during the last 50 years, studied by aerial photos. Landscape Urban Plan. 31: 21-37.

Johnson, E. A. 1979. Fire recurrence in the subarctic and its implications for vegetative composition. Can. J. Bot. 57: 1374-1379.

Johnson, E. A. 1992. Fire and vegetation dynamics: studies from the North American boreal forest. Cambridge University Press, Cambridge, UK. 129 p.

Johnson, E. A., and S.L. Gutsell. 1994. Fire frequency models, methods and interpretations. Adv. Ecol. Res. **25**: 239-287.

Johnson, E. A., and C. E. Van Wagner. 1985. The theory and use of two fire history models. Can. J. For. Res. 15: 214-220.

Johnson, J. D., J. H. Smyth, and G. W. Crook. 1995. Costs of alternate strip cutting and clearcutting in upland black spruce. Natural Resources Canada, Canadian Forest Service – Ontario. Technical Note No. 70. Sault Ste. Marie, ON.

Kotz, S., and N. L. Johnson, editors. 1985. Encyclopedia of Statistical Sciences Vol. 5. John Wiley & Sons, Inc., New York, NY.

Larsen, C. P. S. 1997. Spatial and temporal variations in boreal forest fire frequency in northern Alberta. J. Biogeog. 24: 663-673.

Lorenz, M. O. 1905. Methods of measuring the concentration of wealth. Publications of the American Statistical Association, New Series 9(70): 209-219.

McDermott, G. L. 1961. Frontiers of settlement in the Great Clay Belt, Ontario and Quebec. Ann. Assoc. Am. Geogr. 51(3): 261-273.

Ontario Ministry of Natural Resources. 1986. The forest resources of Ontario 1986. Forest Resources Group, Ministry of Natural Resources. Queen's Printer of Ontario, Toronto, ON.

Ontario Ministry of Natural Resources. 1998. Ontario's forest fire history: An interactive digital atlas. Queen's Printer for Ontario, Toronto, ON.

Parent, S., H. Morin, and C. Messier. 2000. Effects of adventitious roots on age determination in the balsam fir regeneration. Can. J. For. Res. 30: 513-518.

Parent, S., H. Morin, and C. Messier. 2002. Missing growth ring at the trunk base in suppressed balsam fir saplings. Can. J. For. Res. 32: 1776-1783.

Reed, R. A., J. Johnson-Barnard, and W. L. Baker. 1996. Fragmentation of a forested Rocky Mountain landscape, 1950-1993. Biol. Conserv. 75: 267-277

Reed, W. J. 2001. Statistical inference for historical fire frequency using the spatial mosaic. Pages 419-435 in E. A. Johnson and K. Miyanishi, editors. Forest fires: behavior and ecological effects. Academic Press, San Diego, CA.

Reed, W. J., C. P. S. Larsen, E. A. Johnson, and G. M. MacDonald. 1998. Estimation of temporal variations in historical fire frequency from time-since-fire map data. Forest Science 44: 465-475.

Simpson, J. W., R. E. J. Boerner, M. N. DeMers, L. A. Berns, F. J. Artigas, and A. Silva. 1994. Forty-eight years of landscape change on two contiguous Ohio landscapes. Landscape Ecol. 9(4): 261-270.

Spruce Falls, Inc. 2001. Company history. url: http://www.sprucefalls.com

Staaland, H., Ø. Holand, C. Nellemann, and M. Smith. 1998. Time scale for forest regrowth: abandoned grazing and agricultural areas in southern Norway. Ambio 27(6): 456-460.

Stocks, B. J. 1991. The extent and impact of forest fires in northern circumpolar countries. Pages 197-202 in J. S. Levine, editor. Global biomass burning: atmospheric, climatic, and biospheric implications. MIT Press, Cambridge, MA.

Suffling, R., B. Smith, and J. Dal Molin. 1982. Estimating past forest age distributions and disturbance rates in northwestern Ontario: a demographic approach. J. Env. Manage. 14: 45-56.

Thomas, P. A., and R. W. Wein. 1985. The influence of shelter and the hypothetical effect of fire severity on the postfire establishment of conifers from seed. Can. J. For. Res. 15: 148-155.

Troughton, M. J. 1983. The failure of agricultural settlement in northern Ontario. Nordia 17(1): 141-151.

Turner, M. G., and C. L. Ruscher. 1988. Changes in landscape patterns in Georgia, USA. Landscape Ecol. 1(4): 241-251.

Wallin, D. O., F. J. Swanson, B. Marks, J. H. Cissel, and J. Kertis. 1996. Comparison of managed and pre-settlement landscape dynamics in forests of the Pacific Northwest, USA. Forest Ecol. Manag. 85: 291-309.

Weber, M.G., M. Hummel, and C. E. Van Wagner. 1987. Selected parameters of fire behavior and *Pinus banksiana* Lamb. regeneration in eastern Ontario. For. Chron. 63: 340-346.

Weir, J. M. H., E. A. Johnson, and K. Miyanishi. 2000. Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. Ecol. Applic. 10: 1162-1177.

Yarie, J. 1981. Forest fire cycles and life tables: a case study from interior Alaska. Can. J. For. Res. 11: 554-562.

Zasada, J.C., R. A. Norum, R. M. Van Veldhuizen, and C. E. Teutsch. 1983. Artificial regeneration of trees and tall shrubs in experimentally burned upland black spruce/feather moss stands in Alaska. Can. J. For. Res. 13: 903-913.

Zipperer, W. C., R. L. Burgess, and R. D. Nyland. 1990. Patterns of deforestation and reforestation in different landscape types in central New York. Forest Ecol. Manag. 36: 103-117.