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FIRE FREQUENCY AND THE SPATIAL AGE MOSAIC OF THE MIXED-WOOD BOREAL FOREST IN WESTERN CANADA

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Abstract. One approach to ecosystem management is to emulate the effects of natural disturbance in producing landscape patterns; this approach requires a spatial analysis of the pattern and an understanding of the processes producing the pattern. Forested landscapes exhibit mosaic patterns of both stand types and ages. This study investigates the spatial mosaic of stand ages produced by high-intensity stand-replacing fires in the mixed-wood boreal forest of western Canada. A high-resolution, accurately dated, time-since-fire map for a large (3461 km^2) contiguous area is used to produce the landscape survivorship distribution in which both spatial and temporal changes in fire cycle are statistically tested. Spatial multivariate analysis of the time-since-fire map is also used to investigate the spatial assembly of the age mosaic. Significant changes in fire cycle can be explained by climatic change as well as land use change in the surrounding area. The shift from a short (15 yr) fire cycle to a longer (75 yr) cycle after 1890 in the northern half of the study area coincides with climatic change at the end of the Little Ice Age. In the southern half of the study area, the short fire cycle continues after 1890 due to the spread of human-caused fires from the adjacent area which was settled and cleared for agriculture during the first half of the 20th century. Upon completion of settlement in 1945, the fire cycle becomes significantly longer due to the fragmentation of the once continuous forest that surrounded the study area and from which the majority of large fires propagated in the past. The different fire cycle histories of the two parts of the study area also explain the spatial mosaic pattern of stand ages, sizes, and shapes. The extended period of the short fire cycle through the first half of this century in the southern region results in it being dominated by younger, larger, oblong-shaped polygons with irregular edges: characteristics that describe the shapes of large burns. The northern region has generally older and smaller, more circular, compact polygons that are the remnants of larger much earlier burns that have since been overburned. The polygons in the northern region are more similar in size and shape but less similar in age to adjacent polygons than are those in the southern region. Thus, this study shows how spatial heterogeneity in the landscape mosaic pattern can be characterized and related to the disturbance history of an area. Furthermore, it provides evidence of the impacts on the age mosaic due to forest fragmentation in surrounding areas.

Key words: boreal forest; ecosystem management; equilibrium; fire frequency; fire history; forest fires; forest fragmentation; land use change; natural disturbance; Prince Albert National Park, Saskatchewan; spatial statistics.

Introduction

One approach to ecosystem management is to have management practices emulate the effects of natural disturbance, the object being to produce patterns of vegetation and habitats similar to those that would be produced by the natural disturbance regime (Hansen et al. 1991, Runkle 1991, Hunter 1993, Ontario Forest Policy Panel 1993, Galindo-Leal and Bunnell 1995). In order to apply such an approach, we require an understanding of the landscape patterns and how these patterns come about.

Landscapes exhibit mosaic patterns of both community types and ages. For a 3461 km^2 area within the mixed-wood boreal forest in western Canada, Bridge and Johnson (2000) demonstrated the role of surficial geology and geomorphic processes in producing the upland mosaic pattern of species composition and stand types across the landscape. They found that the moisture and nutrient gradients along which species sorted themselves were related to hillslope position and surficial geology. On glacial till, the dominant canopy species were *Populus tremuloides* at the crest, *Abies balsamea* at midslope, and *Picea glauca* at the bottom. On glaciofluvial substrate, the dominant canopy species were *Pinus banksiana* from crest to midslope and *Picea mariana* from midslope to bottom. Thus, the mosaic pattern of stand types could be largely predicted from hillslope geomorphology. Furthermore, since hillslope lengths tend to remain fairly constant regardless of basin size and

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since similar surficial materials produce hillslopes with similar slope profiles, S. R. J. Bridge and E. A. Johnson (*unpublished manuscript*) found that species occupy constant proportions of basin area regardless of basin size. Therefore, they showed how the landscape scale spatial patterns of vegetation distribution could be explained and predicted by linking geomorphic processes at the hillslope and basin scale.

In this paper, we will address the second mosaic pattern, that of stand ages, for the same study area. The age mosaic in this region is created by wildfire (both lightning- and human-caused) and can therefore be represented by a time-since-fire map in which patches or polygons are identified by the time since they last burned. The mosaic pattern is a result of more recent fires overburning areas that had been burned in past fires. Thus, areas representing older burns will not show their original size since parts of them will have since been overburned by more recent fires (see Johnson and Gutsell 1994). Fire frequency can be determined by calculating the percentage of the total map area covered by the different time-since-fire ages and plotting their cumulative distribution which represents the survivorship of the landscape from fire (Heinselman 1973, Van Wagner 1978, Johnson and Gutsell 1994).

Past studies of fire frequency in the boreal forest have demonstrated three important aspects of fire behavior over the landscape. First, they showed that all areas in the landscape have burned at some time in the past and that old growth forests comprise a small percentage of the landscape (Johnson et al. 1995, Lesica 1996). Second, they found that the fire frequency distribution generally fits an exponential model (Van Wagner 1978, Johnson et al. 1990, Masters 1990, Bergeron 1991, Johnson and Larsen 1991, Larsen 1997). Third, most of these studies have produced mixed time-since-fire distributions which indicate temporal changes in fire frequency correlated with climate changes related to the Little Ice Age and/or land use changes in the surrounding landscape (Clark 1988, Bergeron 1991, Johnson and Larsen 1991, Larsen 1997).

Most fire frequency studies have been based on a sampling of study areas and not on an actual time-since-fire map of a large contiguous forested area. In this paper, we present the first fire frequency study of the western mixed-wood boreal forest based on a high resolution (5 ha), accurately dated (within 5 yr), time-since-fire map for a very large contiguous area (3461 km^2). Also, methods have been developed recently for testing the significance of changes in fire frequency, as well as for obtaining estimates of the fire frequencies with confidence intervals during different time periods or epochs (Reed 1994, Reed et al. 1998). We use these methods to provide estimates of fire frequencies with confidence intervals and statistically test changes in fire frequencies to investigate both temporal and spatial differences in fire frequency due to climate change and also landuse change in the surrounding landscape.

While the study area itself has not undergone land use change, the formerly forested areas surrounding the southern half of the study area have been settled and cleared for agriculture in the past century. The human-set fires used to clear the forests adjacent to the study area might be expected to have spread and thus increased the fire frequency of the study area. Furthermore, we hypothesize that the isolation of the study area from continuous forest after the completion of forest clearance for agriculture in the surrounding areas would have caused a decrease in fire frequency. Therefore, we investigated the timing and rate of forest clearance in the surrounding areas, as well as the direction of spread of large fires in this region, in order to relate changes in fire frequency of the study area to landuse change in the surrounding areas.

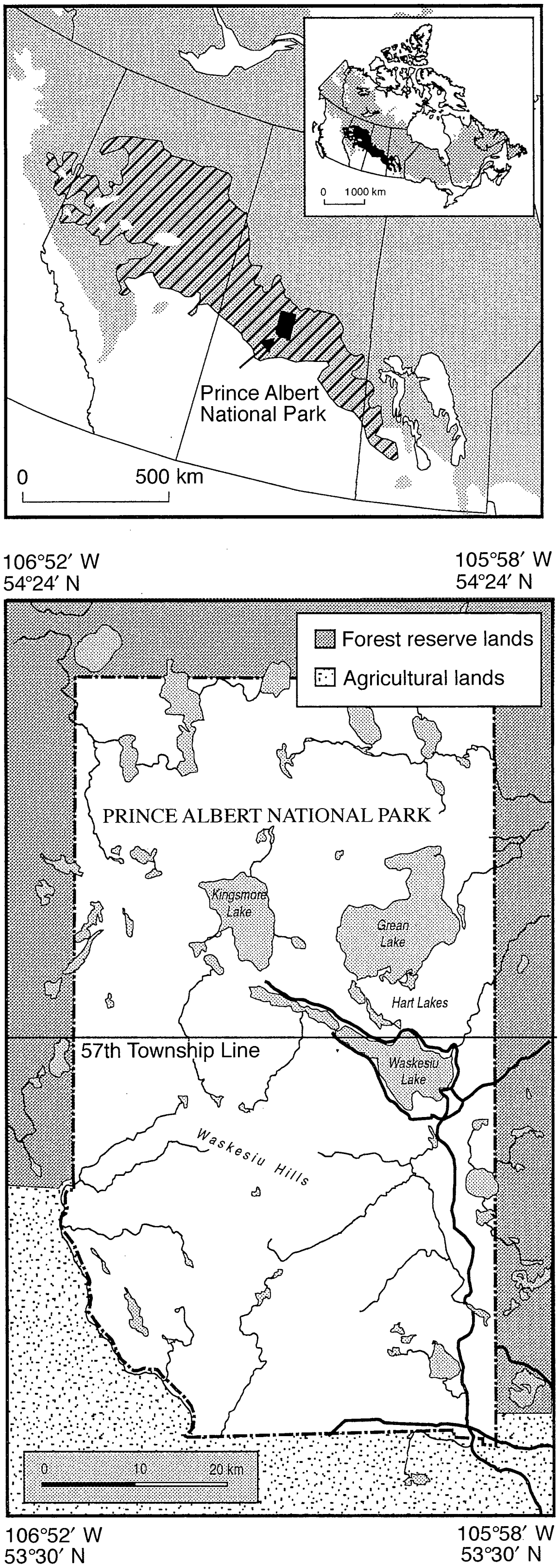
If ecosystem managers are to develop management plans that produce forested landscape patterns similar to those resulting from the natural fire regime, they must be aware of the fact that fire frequencies change naturally as a result of climatic changes, often within the lifespan of the trees, and that the current pattern observed is most likely the product of two or more different fire frequencies. Furthermore, the relative role of humans in influencing fire frequency can only be evaluated in relation to this naturally changing fire frequency.

Time-since-fire maps can also be used to obtain other information about fire-created patterns. In fire frequency studies, the polygons are combined into groups of common age and no use is made of the size or shape of the individual polygons nor how they are spatially arranged on the landscape. In this study, we perform a spatial multivariate analysis on the time-since-fire map to investigate the spatial assembly of the age mosaic (i.e., the spatial structure of the polygons on the time-since-fire map in terms of their age, size, and shape). If the goal of ecosystem management is to maintain the spatial heterogeneity of the age mosaic pattern of the forested landscape, it is obviously essential to know what that mosaic pattern actually is and what factors cause variation in the spatial heterogeneity.

STUDY AREA

The study area is Prince Albert National Park (3461 km^2) in central Saskatchewan, Canada, which is surrounded on the west, north and east by forest reserve lands that are managed principally for pulpwood and sawlogs (Fig. 1). Lands south and southwest of the Park have been cleared for agriculture (Weir and Johnson 1998). Historically, the forest extended 45 km south of the Park (Zoltai 1975).

The Park is located within the mixed-wood boreal forest (Rowe 1972). Upland sites are composed of aspen (*Populus tremuloides* Michx.), white spruce (*Picea glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.), white birch (*Betula papyrifera* Marsh.), balsam



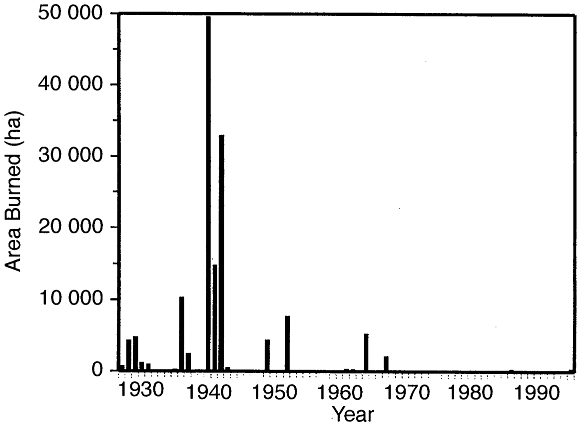


FIG. 2. The distribution of area burned annually in Prince Albert National Park from 1927 to 1995.

poplar (*Populus balsamifera* L.), and balsam fir (*Abies balsamea* (L.) Mill.) (Dix and Swan 1971; Bridge and Johnson 2000). Lowland sites are composed of black spruce (*Picea mariana* (Mill.) B.S.P.), tamarack (*Larix laricina* (Du Roi) K. Koch), swamps, bogs, and fens (Jeglum 1972, 1973).

The study area has a gently to strongly rolling glacial topography, ranging in elevation from 520 to 820 m above mean sea level. Luvisolic soils are characteristic of the upland areas and gleysolic and organic soils are found on poorly drained sites (Ellis and Clayton 1970).

The region has a cool subhumid continental climate (Atmospheric Environment Service 1993) with long cold winters (January mean −18.9°C) and short hot summers (July mean +16.3°C). The majority (256 mm) of the annual precipitation of 455 mm falls from June through September.

Wildfires occur from April to September with 90% of the area burned occurring in May and June (Johnson et al. 1999). As in other areas of the boreal forest, fires tend to be high intensity, stand-replacing, crown fires caused primarily by lightning (Johnson 1992). Surface fires do not account for a significant proportion of the area burned. Years during which large areas are burned occur infrequently and are separated by years with little area burned (Fig. 2). The infrequent nature of years with large areas burned appears to be controlled by the development of persistent blocking high pressure systems (Stocks and Street 1983, Flannigan and Harrington 1988, Bergeron and Archambault 1993, Johnson and Wowchuk 1993, Nash and Johnson 1996). At least three times in the last 235 years over 25% of the study

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FIG. 1. The study area of Prince Albert National Park located within the mixed-wood boreal forest (indicated by hatching in top panel) in central Saskatchewan. The 57th township line marks the boundary between the north and south regions of the park.

area was burned by a single fire. In 1890 the largest known fire in the study area burned approximately 200 000 ha within the park as well as an unknown area beyond the present park boundary.

METHODS

Time-since-fire map

Black and white aerial photographs (taken in 1947 and 1990 at a scale of 1:12 500, in 1968 at a scale of 1:15 000, and in 1976 at a scale of 1:40 000) were used to identify 3168 preliminary time-since-fire polygons. All polygons identified were visited to confirm their boundaries and to collect data for obtaining the date of the most recent fire.

Three types of field evidence were used to date fires: disks from fire-scarred trees, cores from remnant trees (that survived the fire but were not scarred), and cores from canopy trees. Fire-scarred trees (which are usually found along fire boundaries and less frequently within polygons) were felled and a disk was collected from the base of the tree. Increment cores (that included the tree's pith) were extracted from the base of remnant trees and at least five canopy trees within each polygon. Tree disks and increment cores were sanded and analyzed in the lab, not in the field. Ring counts were performed along three axes of each fire-scarred disk to eliminate error associated with locally absent or indistinct growth rings. Immediately after a fire, remnant trees often experience increased diameter growth that is sustained for 10 or more years. Canopy trees that would have established immediately after the fire had to show rapid growth following establishment and present no evidence of growth release. Thus, the age of the canopy trees, fire-scar dates and date of growth release in remnant trees within a polygon were used together to establish the date of the most recent fire. Disks with multiple fire scars were also used to confirm the fire dates of adjacent polygons. In addition, fire reports prepared by the park since 1927 were used to identify fire ages and area (although fire maps only approximated fire perimeters and rarely identified areas within the perimeter that did not burn). No successional, tree composition, or height arguments were used to infer ages. Fire dates after 1700 are accurate to the year while those before 1700 are accurate within 5 years, based on the degree of consistency of the various forms of evidence used to determine the fire date.

The final time-since-fire map was produced by transferring polygon boundaries from orthocorrected air photos to a 1:50 000 topographic map using a zoom transfer scope. Extensive ground truthing of the preliminary polygons identified on 1:12 500 air photos allowed detection of polygons (with accurate boundaries) as small as 5 ha. Following ground truthing of each polygon and determination of fire dates, the 3168 preliminary polygons were reduced to 1249 polygons, representing separate fire dates, whose boundaries were verified. Accurate measures of the areas in different times-since-fire are required for the fire frequency distribution. Since the topographic relief within the study area is only 300 m, simple planar area as measured directly from topographic maps was considered to be an accurate measure of actual surface area (see Johnson and Larsen 1991).

Fire frequency analysis

Fire dates were grouped into five year classes to reflect the accuracy of the older time-since-fire dates. The areas of all polygons within each fire date class were combined to produce the cumulative time-since-fire distribution which was plotted on semi-log paper. The data were partitioned spatially a number of ways (by vegetation type, surficial geology, slope position, and aspect as well as along township lines) in order to find spatial differences in fire frequency. Within regions with spatially homogeneous time-since-fire distributions, the mixed distributions were analyzed for temporal changes in fire frequency (see Johnson and Gutsell [1994] for flowchart).

The parameters of these temporally mixed time-since-fire distributions were estimated using methods described by Reed et al. (1998). The time period between change point dates (dates when fire frequency changed) are called epochs. The methods assume: (a) that the homogeneous time-since-fire distributions of the epochs fit the negative exponential model (Johnson and Van Wagner 1985), (b) that the change points, P_i, are identified independent of the time-since-fire distribution, (c) that the hazard of burning changes instantaneously at the change point date, and (d) that a forest originating in the oldest epoch experienced its hazard of burning as well as that of each of the subsequent epochs. Two change points were identified: 1890, which marks the end of the Little Ice Age (Heusser 1956, Brunger et al. 1967, Luckman 1977, Luckman and Osborn 1979, Grove 1988); and 1945, which marks when the area south of the park was largely settled and converted to agriculture.

Thus, we hypothesize that the time-since-fire distribution, $A(t)$, has two change points and three epochs that can be expressed as follows:

$$A(t) = \begin{cases} \exp(-\lambda_1 t) & 0 \le t < P_1 \\ \exp(-\lambda_1 P_1 - \lambda_2(t - P_1)) & P_1 \le t < P_2 \\ \exp(-\lambda_1 P_1 - \lambda_2(P_2 - P_1) - \lambda_3(t - P_2)) & \\ & P_2 \le t \end{cases} \tag{1}$$

where t is time-since-fire, P_1 and P_2 are the dates of the most recent and most historic change points respectively, and λ_i is the hazard of burning during the ith epoch, $i = 1, 2, 3$ (recent to historic). An epoch's hazard of burning was estimated using the Maximum Likelihood Estimate of the probability of surviving from one age class to another (Reed et al. 1998). The hazard of burning during an epoch can also be expressed in terms of the region's fire cycle, $1/\lambda$, which is the length of time (years) taken to burn an area equal in size to the study area. The 95% confidence interval of the hazard of burning (and its inverse, the fire cycle) for each epoch was determined by means of a likelihood ratio procedure described by Reed et al. (1998). The degrees of freedom for the critical F value is the number of age classes minus one minus the number of epochs. The calculation of the confidence intervals takes into account that the probability of an area burning is not independent of an adjacent area (since fires burn contiguous parts of the landscape) by incorporating the overdispersion parameter, σ^2, which can be determined using either Pearson's estimate or the residual deviance estimate (Reed 1994).

The difference between the distributions of adjacent epochs can be tested for a sequence of nested models by constructing an analysis of deviance table (Reed et al. 1998). Two models are hypothesized, in which the null hypothesis is nested within the alternate hypothesis, and the difference of these models is tested. For example, to test the difference between epochs 1 and 2 in a distribution with two partition dates (P_1 and P_2) and three epochs, the parameters of the null hypothesis are calculated using a model with one partition date, P_2, while the parameters of the alternative hypothesis are calculated using a model having two partition dates, P_1 and P_2. The quasi-deviance of the models, D_0 and D_1, is calculated and the difference in quasi-deviance, $D = D_0 - D_1$, indicates the discrepancy of the data in favor of the alternative hypothesis, H_1. D is scaled by the estimate of the overdispersion parameter to determine the test statistic, $D^* = D/\sigma$, that is compared to an F distribution to obtain the appropriate P value (for details of this analysis, see Reed et al. 1998).

Landuse change in the surrounding area

In order to investigate the possible effects of landuse change and forest fragmentation in the surrounding area on the fire frequency of the study area, it was necessary to document the extent and timing of such landuse changes so they could be related to changes in fire frequency in the study area. The presettlement vegetation of the agricultural region surrounding the southern half of Prince Albert National Park (Fig. 3) was determined from township plats which were compiled from field notes of Dominion Land Surveyors (Glenbow-Alberta Institute Archives, Calgary, Alberta, Canada). A presettlement vegetation cover map was produced by classifying the township vegetation descriptions into open and closed canopy forest types. The closed canopy types were further classified into pure deciduous forest or mixed-wood forest dominated by either deciduous (*Populus tremuloides, P. balsamifera, Betula papyrifera,* and *Salix* spp.) or coniferous (*Picea glauca, P. mariana, Pinus banksiana,* and *Abies balsamea*) species. The open canopy forest types were further classified into sparsely stocked deciduous-dominated mixed-wood forest or shrub cover.

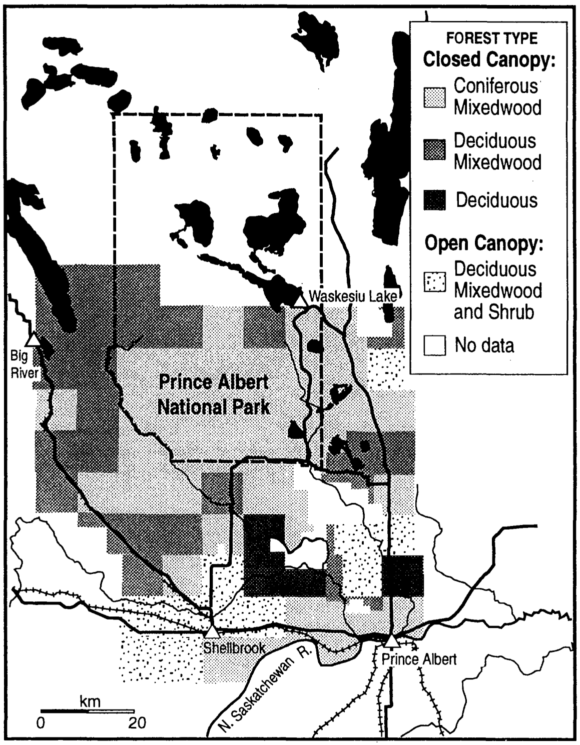

FIG. 3. The presettlement forest cover of the south region of Prince Albert National Park and surrounding areas as determined from field notes of Dominion Land Surveyors.

A vegetation cover map for 1963 was produced using aerial photographs taken at a scale of 1:40 320. The vegetation cover was classified into open and closed canopy forest, grassland, and agricultural types. The grassland type included nonagricultural lands dominated by graminoids. The agricultural type included cultivated lands, mowed hay meadows, and grazed livestock pastures.

Maps showing the extent of agriculture, and hence forest fragmentation, between 1900 and 1963 were prepared using forest conversion rates based on information contained in the homestead records (Saskatchewan Archives Board, Regina, Saskatchewan, Canada). The homestead records identify when a settler claimed and began to reside on a particular 160 acre (64.8 ha) homestead (the claimed date), and when the land's patent was transferred to the settler (the patent date). Between the claimed and patent dates, the settler had to meet the conditions required by the Homestead Act to obtain the homestead's patent. Prior to 1908, the Act required that 15 acres (6 ha) be converted to agricultural land and cultivated for three consecutive years (Allen 1889). After revision in 1908, the Act required a settler to convert 30 acres (12 ha) to agricultural land and to reside on the land for at least three consecutive years. In 1930, the administration of Crown lands was transferred to the Province of Saskatchewan and the new Saskatchewan Homestead Act of 1935 was applied to all homesteads filed between 1930 and 1940. After 1940, all Crown lands were excluded from settlement and the Saskatchewan Homestead Act was cancelled (Fitzgerald 1965).

For each of the 2928 homesteads filed in the surrounding agricultural region, the overall rate of conversion (CR) in acres per year from presettlement vegetation to agriculture was calculated by

$$\text{CR} = (\text{Area converted at the patent date}) \div (\text{Patent date} - \text{Claimed date}). \quad (2)$$

An additional three years was subtracted from the denominator for homesteads filed before 1908.

Conversion rates for each homestead were also calculated for each of four settlement periods (CR_I) where $I = 1$ (1930–1940), $I = 2$ (1920–1930), $I = 3$ (1908–1920), and $I = 4$ (before 1908). With the exception of 1920, the dates correspond to changes in the Homestead Act. The area of a homestead (acres) under agriculture at any given date (A_t) was calculated by:

$$A_t = \text{Area at patent date} + \Sigma(\text{CR}_I T_I) \quad (3)$$

where T_I is the number of years in each settlement period (I):

$$T_1 = t - 1930 \text{ or patent date} \quad \text{if patent date} \geq 1930$$

$$T_2 = t - T_1 - 1920 \text{ or patent date} \quad \text{if } 1930 > \text{patent date} \geq 1920$$

$$T_3 = t - (T_1 + T_2) - 1908 \text{ or patent date} \quad \text{if } 1920 > \text{patent date} \geq 1908$$

$$T_4 = t - (T_1 + T_2 + T_3) - \text{patent date} \quad \text{if } 1908 > \text{patent date}.$$

The calculations assume the conversion rate after 1940 is the same as that from 1930 to 1940. The percentage of a homestead that was in agriculture at any given date was calculated by dividing the area in agriculture at that date (A_t) by 160 (i.e., the total area of each homestead). Differences in the average conversion rates between decades were tested using Tukey's test.

Using the provincial base map to identify homesteads, maps were prepared showing the percentage of homesteads that were in agriculture for each decade from 1900 to 1960 and for 1963. The 1963 map was then compared to the actual distribution of agricultural land identified from the 1963 aerial photographs.

Reports of wildfires that burned into the Park from the agricultural region were only available from 1927 to 1995 (National Archives of Canada, Ottawa, Ontario, Canada). Data on the point of ignition, date of occurrence, cause, date of extinguishment, and final size of fire were obtained from 332 reports and maps. No fire reports prior to 1927 were available.

The study area is too small to provide a large enough sample of fires >100 ha from the 1927–1995 fire reports. Consequently, to study the spread of large fires, we analyzed a set of data obtained from fire reports for 54 fires >100 ha (some as large as 100 000 ha) that occurred across a large area of mixed-wood boreal forest in central Saskatchewan from 1980 to 1992 (Saskatchewan Environment and Resource Management, Saskatoon, Saskatchewan). These fires burned in the same type of forest and are influenced by the same weather systems as fires in the study area. The direction and distance of spread for these fires were determined by drawing a line on the fire map between the fire's ignition point and the furthest point burned.

Spatial multivariate analysis

The variables used in the Spatial Multivariate Analysis (SMA) of polygons in the time-since-fire map were of three types: age, size, and shape. The age variable (v_1) is the time-since-fire age for each polygon and the size variable (v_2) is the area of each polygon. The four shape variables used included the following:

v_3 (form ratio)

$= (4 \cdot \text{area})/(\pi \cdot \text{longest length of polygon}^2)$,

which varies from 0 (linear) to 1 (circular);

v_4 (circularity)

$= (4\pi\text{area})/\text{perimeter}^2$,

which varies from 0 (oblong) to 1 (circular);

v_5 (compactness)

$= \text{area}/(\pi \cdot \text{longest radius}^2)$,

which varies from 0 (compact with smooth circumference) to 1 (highly convoluted circumference); and

v_6 (radius ratio)

$= \text{shortest radius}^2/\text{longest radius}^2$,

which varies from 0 (irregular) to 1 (circular).

A large number of other variables could have been used (see McGarigal and Marks 1994). However, these four variables were selected as they met our objective of describing the shape of the polygons in terms of their general shape or form, circularity, compactness, and regularity of shape with a minimum of redundancy.

SMA (Wartenberg 1985) is similar to Principal Components Analysis (PCA) but uses a spatial correlation coefficient (Moran's I) instead of a Pearson's correlation coefficient (r) (Cliff and Ord 1981). Moran's I is a correlation coefficient with the addition of a weighting factor which describes the spatial relationship between polygons. It is the weighted sum of the product of separate data observations centered to the mean of the observations ($\mu = 0$), standardized to adjust for the variance ($\sigma = 1$), and normalized for the total sum of the weights. Moran's I is bounded by $-1 \leq I \leq +1$, where $I = \pm 1$ implies that the values of a variable for polygons which share a boundary are correlated.

If we define each observation (polygon) as a vector of individual observations of m variables, we can define a matrix of coefficients, $\mathbf{M} = \mathbf{Z}'\mathbf{W}\mathbf{Z}$, where $\mathbf{M}$ is an $m \times m$ (variable by variable) spatial correlation matrix, $\mathbf{W}$ is an $n \times n$ (locality by locality) weight matrix (defining adjacent polygons with the weights being 1 for adjacent polygons and 0 for all others), $\mathbf{Z}$ is an $n \times m$ (location by variable) standardized and centered (by variable) data matrix, and $\mathbf{Z}'$ is its transpose. Each diagonal element of the matrix $\mathbf{M}$ gives the correlation of a single variable between adjacent polygons while each nondiagonal element is a bivariate cross-correlation coefficient (the spatial correlation of one variable with another variable calculated by summing the values over all pairs of locations and weighted as in the autocorrelations). The diagonal elements are Moran's I coefficients and the nondiagonal elements are cross correlations between variables i and j, weighted by their location 0 or 1.

The matrix $\mathbf{M}$ was decomposed into orthogonal components using eigenvector analysis. These components reflect the distribution of spatially weighted variation throughout the multivariate field. As in PCA, the first component explains the maximum amount of variance explainable by a linear combination of the original variables. The second component explains the maximum amount of residual variance (not explained by the first component) that is explainable by a linear combination of the original variables, while remaining orthogonal to the first component, etc. The component loadings are the correlations of the original variables with these orthogonal axes. The axes retained as significant were rotated using the Harris-Kaiser oblique method and the locality scores were derived by projecting the original data points onto these rotated component axes. The structure of the axes reflects the coincidence of spatially important (i.e., highly weighted) variables while the locality scores show the contributions of the individual samples to this structure (i.e., which localities are most important in determining this structure). The factor scores for the polygons were then mapped to show regional or landscape level patterns in the spatial patterning of polygons.

RESULTS

Fire frequency analysis

During the last 235 years, all of Prince Albert National Park has been burned at least once. The park's time-since-fire distribution (Fig. 4a) indicates that fire is a relatively frequent disturbance with <5% of the study area older than 125 years. The time-since-fire distribution is mixed both spatially and temporally. The only spatially significant division of the time-since-fire distribution was the division of the Park at the 57th township line into a north and south region of 1563 and 1898 km^2 respectively (Fig. 4b, also see Fig. 1). Subsequent analyses were carried out separately for the time-since-fire distributions of these two regions.

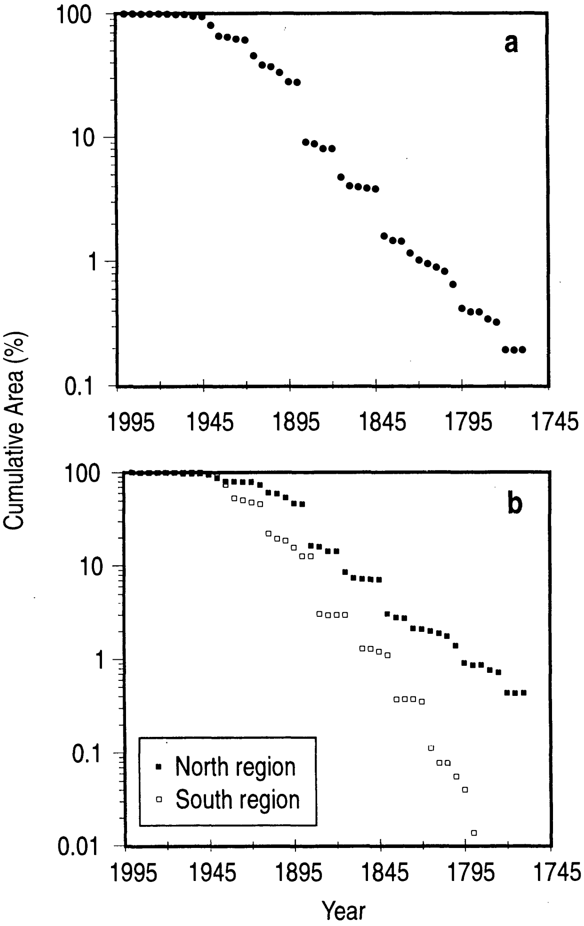

FIG. 4. The time-since-fire distributions for (a) Prince Albert National Park and (b) the north and south regions of the park separately. Data were grouped into 5-yr age classes.

The Pearson's estimate of the overdispersion parameter of both the north and south time-since-fire distributions was larger than the deviance estimate, 4.60 vs. 2.99 and 3.90 vs. 2.85 respectively. Therefore, the Pearson's estimate was used to compare the time-since-fire distributions of adjacent epochs within regions as its larger value would make it less likely to conclude that epochs are different (i.e., it provides a more conservative test). The 95% confidence intervals (CI) around the estimates of the fire cycle were also calculated using the Pearson's estimate.

The time-since-fire distribution of the north region consists of three epochs delineated by two partition dates, 1890 and 1945. Prior to 1890, the fire cycle was shorter (15 yr, CI = 10–35 yr) than between 1890 and

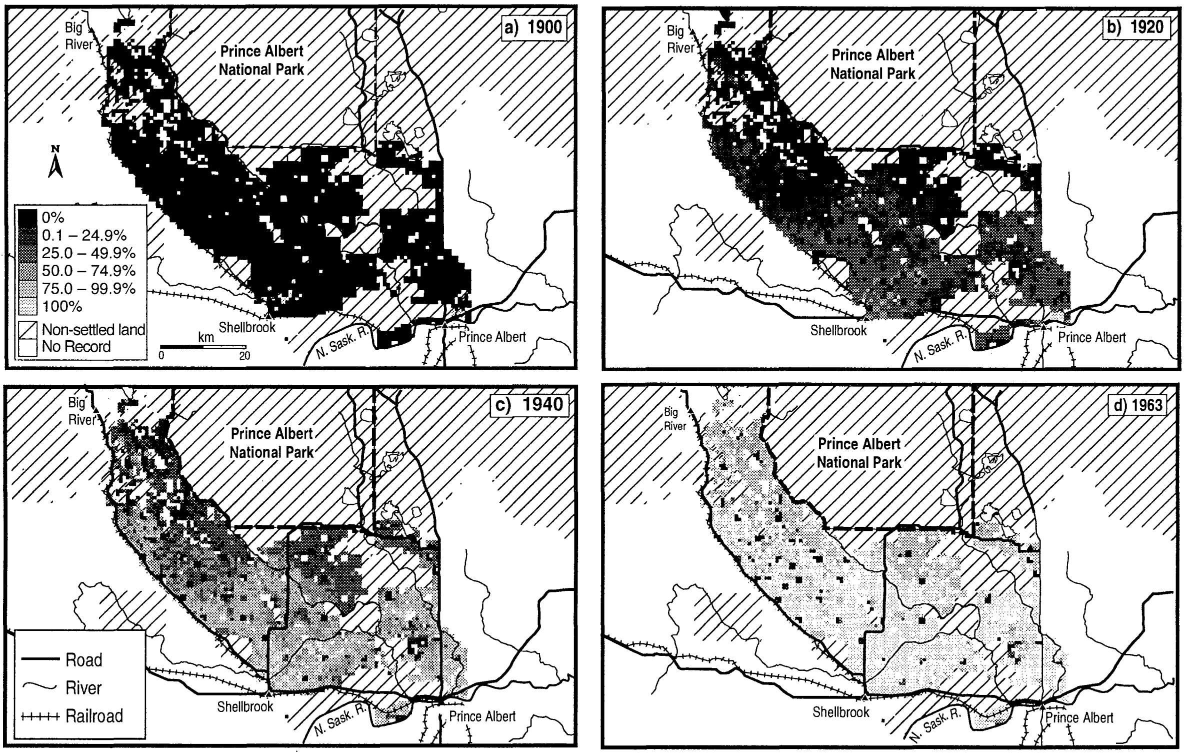

FIG. 5. The percentage of agricultural land that comprised a homestead in (a) 1900, (b) 1920, (c) 1940, and (d) 1963 for the 2928 homesteads in the agricultural region adjacent to Prince Albert National Park, based on calculated conversion rates.

1945 (75 yr, CI = 45–150 yr). Since 1945, the fire cycle has increased to 1,745 yr (CI = 285–127 225 yr). The fire cycle estimates of these three epochs were significantly different ($P < 0.0005$). The time-since-fire distribution of the south region was initially divided into three epochs; however, the fire cycle estimates for the epochs 1795–1890 and 1890–1945 were not significantly different ($P > 0.05$). The change in 1890 to a longer fire cycle seen in the north region did not occur in the south region. Therefore, the fire cycle estimates for the south region were calculated using one partition date of 1945. Prior to 1945, the estimated fire cycle was 25 yr (CI = 15–40 yr) while after 1945, the estimated fire cycle was 645 yr (CI = 200–4270 yr). These estimates were not significantly different ($P > 0.05$) from those for the north region for the epochs prior to 1890 and after 1945 respectively.

Landuse change in the surrounding area

The differences between the time-since-fire distributions of the north and south regions of the park (Fig. 4b) are hypothesized to be due to landuse change in the areas adjacent to the south half of the park. Prior to settlement, the agricultural region surrounding the south half of the Park was almost completely covered by closed canopy mixed-wood boreal forest (Fig. 3). Settlement was initiated in 1890 and the majority of homesteads were claimed between 1900 and 1930. Homesteads that were readily accessible and covered by open canopy deciduous forest were claimed first (Fig. 5, also see Fig. 3). Settlement progressed along a relatively uniform front from the south and southwest toward the north and northeast. The last homesteads to be claimed were located in the agricultural region's northwest and northeast corners adjacent to Prince Albert National Park.

The average conversion rates of the first three settlement periods were significantly different ($P < 0.05$), but there was no difference between the 1920–1930 and 1930–1940 periods. The average conversion rate per homestead increased from 5.19 acres per year prior to 1908 to a maximum of 5.59 acres per year in the period 1908–1920. Following 1920, the average conversion rate decreased to a minimum of 4.34 acres per year between 1930 and 1940. Although the average conversion rates for the settlement periods were significantly different, the absolute differences were small. The overall conversion rate per homestead from 1890 to 1940 was 5.09 acres per year.

Between 1940 and 1950 the total percentage of land cleared for agriculture increased from 56% to 76% (Fig. 6). During this period, the most recently homesteaded and least developed areas were located adjacent to the Park (Fig. 5c).

Comparison of the 1963 map (Fig. 5d), which was based on conversion rates per homestead, to the 1963

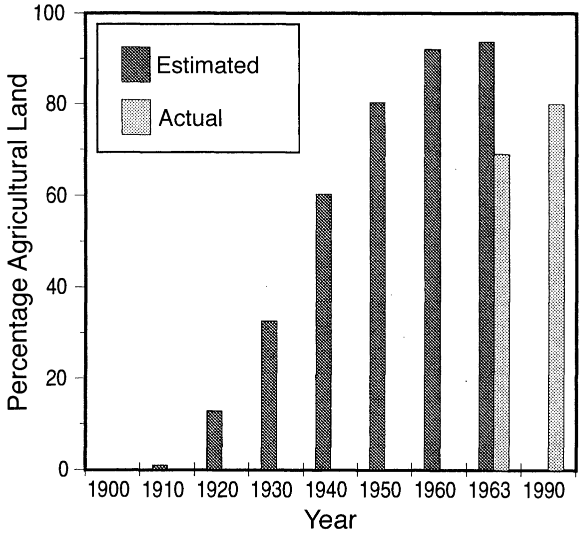

FIG. 6. The total percentage of land cleared for agriculture of all homesteaded lands shown at 10-yr intervals and at 1963. Solid bars represent values calculated using average conversion rates of the various settlement periods. Shaded bars represent actual values obtained from air photo interpretation.

vegetation cover map (Fig. 7), which used aerial photographs to identify vegetation, showed that the location of agricultural and forested lands generally agreed. Using the average conversion rates of the settlement periods, 92% of homesteaded lands in the agricultural region were predicted to be cleared for agriculture by 1963. The actual cover of agricultural land on the 1963 aerial photographs was 69% (Fig. 6). This overestimation of the extent of agriculture is attributable to the assumption that all homesteads were eventually completely converted to agriculture. However, Stutt and Van Vliet (1945) showed that homesteads in this region were on average only 80–88% arable.

Settlement-caused fires burned into the park more frequently between 1927 and 1940 than they have since 1940 (Fig. 8). These settlement-caused wildfires originated on lands located immediately adjacent to the park.

Seventy percent of the large wildfires that burned in the mixed-wood boreal forest of Saskatchewan between 1980 and 1992 spread in a northerly direction, 292.5° to 67.5° (Fig. 9a) and these fires were larger than those that spread to the south (Fig. 9b). Large wildfires frequently spread 25 km from their point of ignition and occasionally as far as 45 km.

Spatial multivariate analysis

Simple observation of the time-since-fire map suggests a pattern of smaller, rounder, older polygons embedded within larger, oblong, younger polygons. These observations are supported by the results of the SMA of the time-since-fire polygons which provides infor-

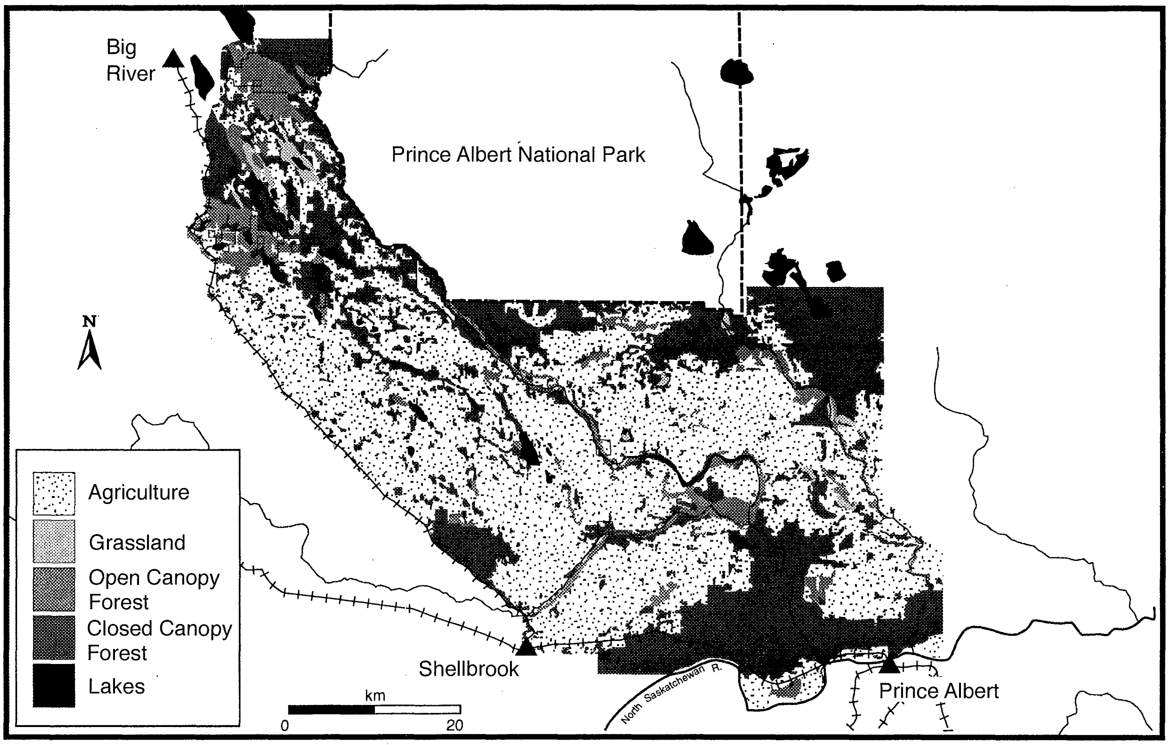

FIG. 7. Vegetation cover of the agricultural region adjacent to Prince Albert National Park as determined by interpretation of 1963 air photos.

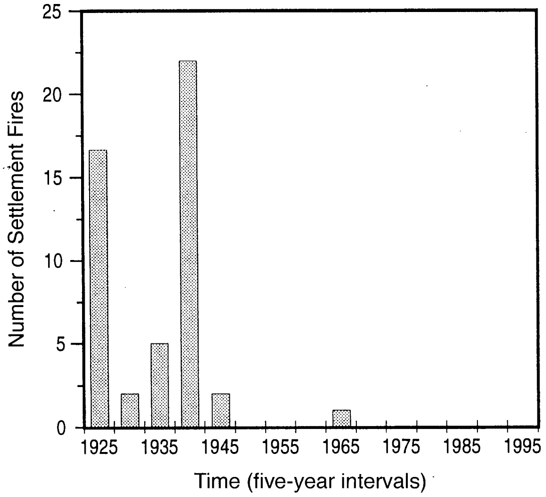

FIG. 8. The number of settlement-caused fires >10 ha that spread into the forested region from 1925 to 1995 at 5-yr intervals (the time interval labeled 1925 only includes fires that burned from 1927 to 1929).

mation on the similarity of adjacent polygons in terms of the age, size, and shape variables.

The first principal component of the SMA has an eigenvalue of 4.21 and accounts for 70% of the variation, while the second principal component has an eigenvalue of 1.22 and accounts for an additional 20% of the variation. The remaining components were not significant by the Scree test.

The first component is defined by a large negative loading for the area variable and large positive loadings for all of the shape variables. The scores of the polygons along this axis are low for large oblong irregular shaped polygons and high for small circular compact polygons, which means that the large oblong polygons tend to be less similar in size and shape to their adjacent polygons than are small circular polygons. As shown by the map of the first principal component scores (Fig. 10), the southern region is dominated by large oblong polygons while the northern region is generally dominated by smaller, more circular polygons.

The second component is defined by a large positive loading for the age variable which means that younger polygons are more similar in age to adjacent polygons than are older polygons. As shown by the map of scores for this second component (Fig. 11), the two highest classes of scores are found only in the southern region, suggesting that, for a significant portion of the southern region, polygons are younger and more similar in age to adjacent polygons than are those in the northern region.

Thus, polygons in the north are smaller, more circular, and more similar in size and shape but less similar in age to adjacent polygons than are the polygons in the south which are larger, more oblong, and less similar in size and shape but more similar in age to adjacent polygons.

DISCUSSION

In the past, attempts were made to determine the minimum size of study area required to obtain a reasonable estimate of disturbance frequency, given the size of disturbances (e.g., Shugart and West 1981, Johnson and Van Wagner 1985, Baker 1989, Turner et al. 1993). These studies used scaling methods to develop some arbitrary rules of thumb (e.g., Shugart and West [1981] proposed a ratio of 1:50 for the disturbance size to study area). In fact, the issue of determining adequate sampling size in any type of study is essentially dependent on the variance. By developing a method of

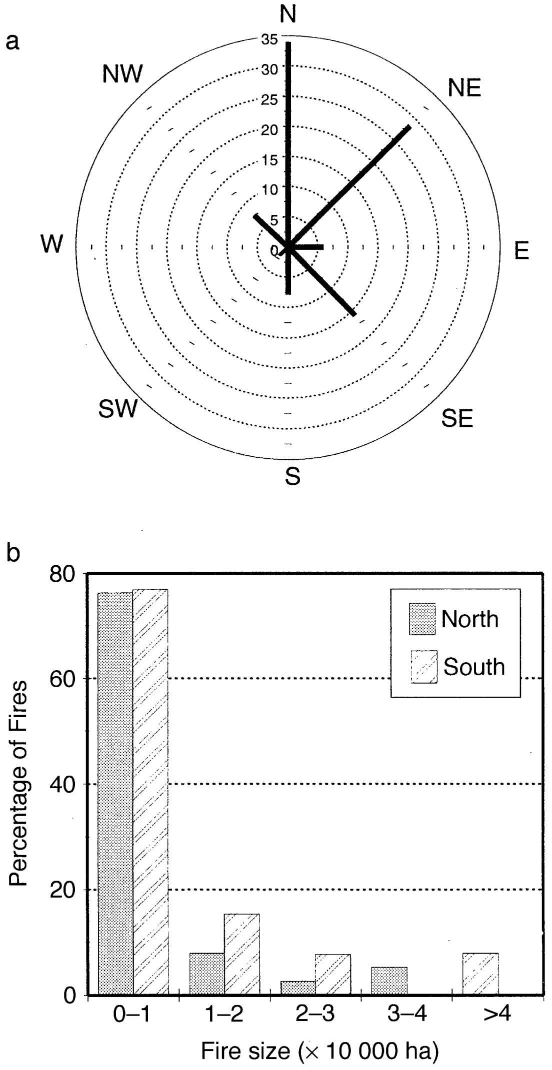

FIG. 9. (a) The percentage of fires that spread in a given direction and (b) the size distribution of north- and south-spreading fires, based on records for fires >100 ha that burned in the mixed-wood boreal forest of Saskatchewan between 1980 and 1992.

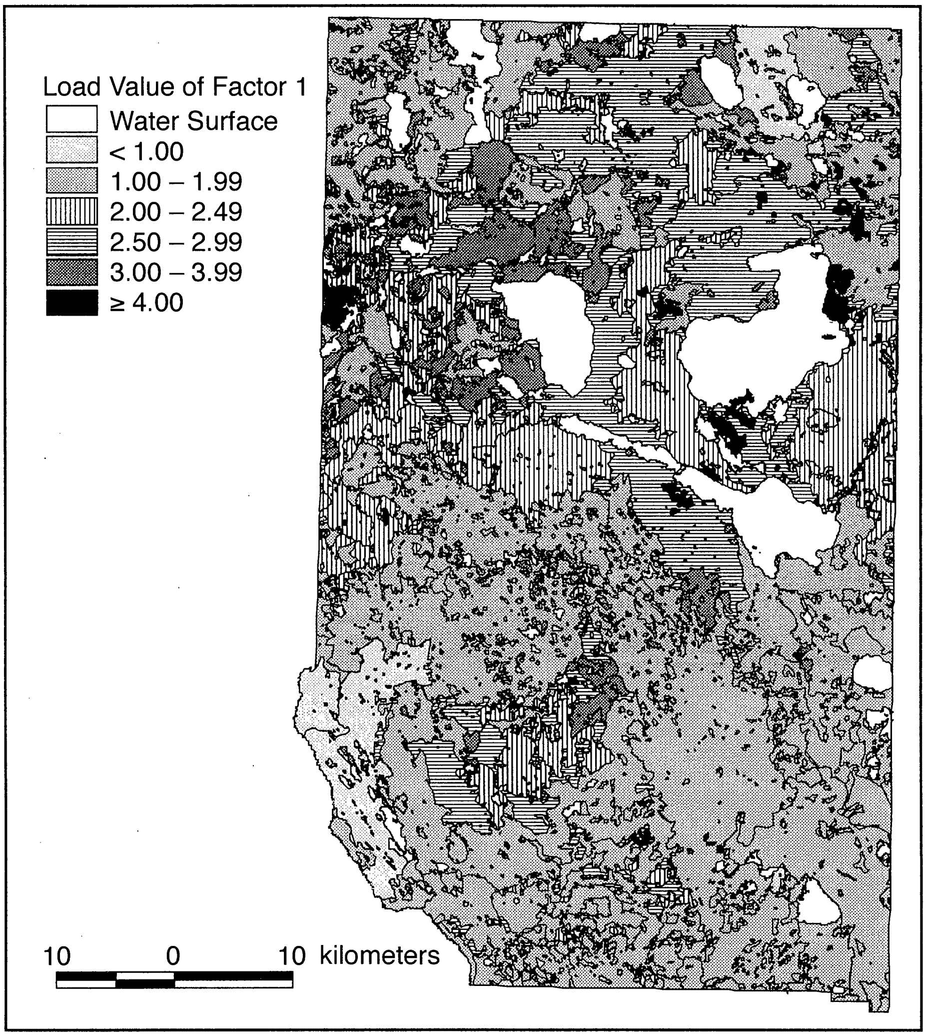

FIG. 10. Map of Prince Albert National Park showing polygon SMA scores for the first principal component. Scores are low for large oblong irregular shaped polygons that are least similar in size and shape to adjacent polygons and high for small circular compact polygons that are most similar to adjacent polygons.

calculating confidence intervals for the parameter estimates of the fire frequency distribution, Reed et al. (1998) provided, for the first time, a statistical method for determining if the size of the study area is large enough relative to the size of disturbance and also if the temporal period covered by the study is long enough relative to the length of the fire cycle to obtain a reliable estimate of fire frequency. If the study area is too small or the temporal period of the study is too short for the size or frequency of disturbance, the confidence interval for the fire frequency estimate is extremely large (as shown in this study by the confidence intervals for the post-1945 period). Furthermore, the ability to determine confidence intervals for the parameter estimates also provides a means of testing the statistical significance of spatial or temporal changes in fire frequency.

As shown in other fire frequency studies in the boreal forest (e.g., Johnson 1992), this area of the western mixed-wood boreal forest has experienced fairly frequent changes in fire cycle (two significantly different fire cycles in the southern region and three in the northern region over the past 200 years). These changes in fire cycle have important implications with respect to mimicking natural disturbance through management for not only is the present age mosaic pattern a product of different fire cycles but also it does not reflect any single "natural" fire cycle for the region.

Prior to 1890 (i.e., during the cool, moist climate of the Little Ice Age), the fire cycle for the whole park was very short, 15–25 yr. After 1890, the fire cycle increased to 75 yr in the northern region. This change in fire cycle is coincident with the end of the Little Ice Age and has been found in a number of other fire frequency studies of coniferous forest across North America (Heinselman 1973, Johnson 1979, Yarie 1981, Suf-

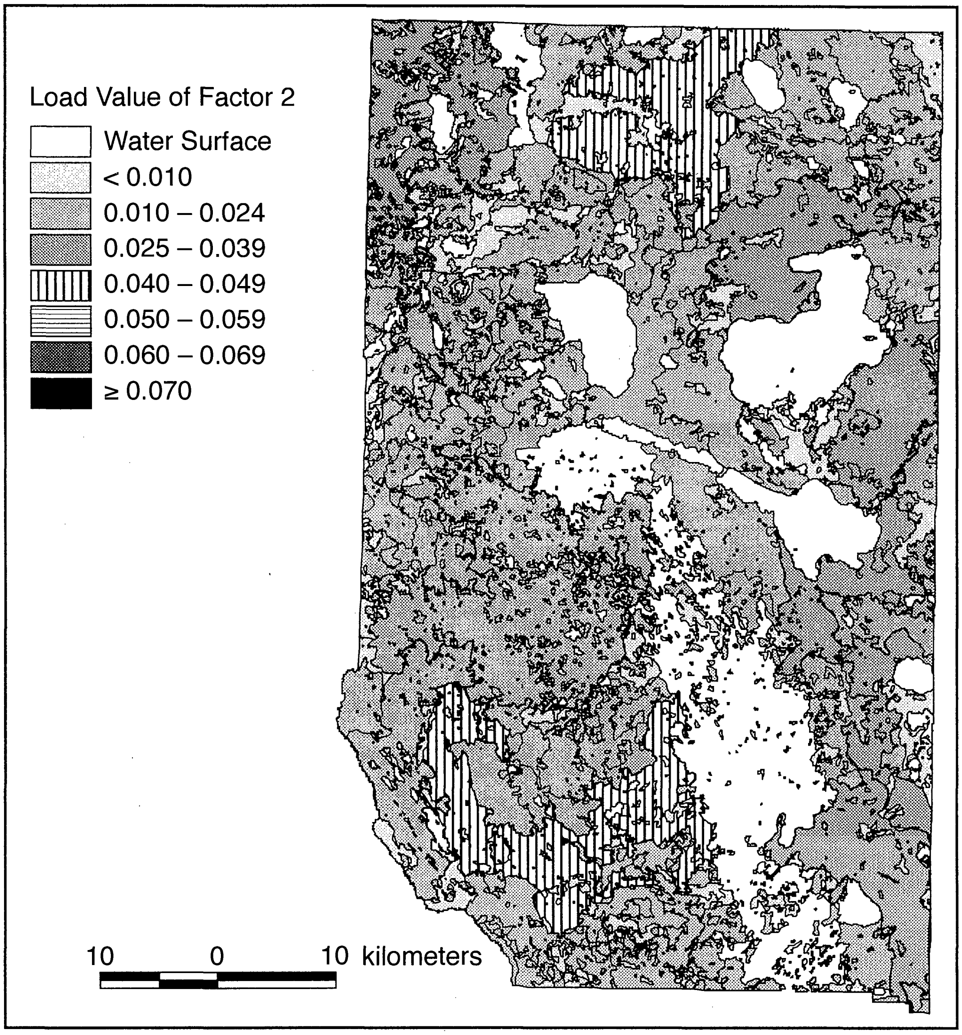

FIG. 11. Map of Prince Albert National Park showing polygon SMA scores for the second principal component. Scores are low for younger polygons that are least similar in age to adjacent polygons and high for older polygons that are most similar to adjacent polygons.

fling et al. 1982, Bergeron 1991). The change we found from a shorter to a longer fire cycle is contrary to what one would expect; i.e., we would expect the cool moist weather of the Little Ice Age to result in a longer fire cycle. However, Bergeron and Archambault (1993) pointed out that this short fire cycle was common in the southern boreal forest during the final part of the Little Ice Age. They suggested that the decreased frequency of persistent blocking high pressure since the end of the Little Ice Age may explain the decreased fire frequency. Persistent blocking high pressure systems are strongly correlated with the development of large wildfires (Stocks and Street 1983, Flannigan and Harrington 1988, Johnson and Wowchuk 1993, Nash and Johnson 1996).

The long fire cycles in both the north and the south regions (1745 and 645 yr, respectively) after 1945 are difficult to evaluate. The extremely large and overlapping confidence intervals around the estimated fire cycles for both regions (285–127 225 and 200–4270 yr, respectively) indicate that these fire cycles are not very precise estimates and that they do not differ significantly between the north and south regions. Consistent with these large confidence intervals, the occurrence of even a relatively small fire would result in a large change in the estimated fire cycle (e.g., a relatively small 3000 ha fire in 1996 changed the current fire cycle estimate by 600 yr).

The time-since-fire distributions also indicate that old age stands do not form a significant proportion of the mixed-wood boreal forest. The entire 3461 km^2 study area has burned in the past 235 years and less than 5% of the area has gone more than 125 years without a fire (Fig. 4a). With the possible exception of *Populus tremuloides,* the probability of a stand surviving beyond the longevity of the tree species and hence showing signs of canopy breakup and gap-phase replacement is very small.

Changes in the fire cycle are expected to have implications for the species composition of the forest. Short fire cycles tend to favor species with either short prereproductive periods (such as *Pinus banksiana*) or vegetative reproduction (such as *Populus tremuloides*) in those sites suitable for these species. Not only the age mosaic pattern but also the species composition mosaic would be expected to reflect the effects of the past as well as the present fire regime.

The change to a significantly longer fire cycle after 1890 (due to climate change) seen in the north part of the Park is not evident in the south, which showed no change in fire cycle between 1795 and 1945. We suggest that this lack of fire cycle change (with the fire cycle remaining short) was a result of landuse change in the area surrounding the south part of the park. The southern fringe of the boreal forest in North America generally marks the boundary of agricultural settlement. North of this fringe, the climate and soils are increasingly unsuitable for farming. Consequently, the fringe is also the site of the fairly recent shift in landuse from a wildland landscape (forest) to a cultural landscape (agriculture). The creation of this cultural landscape and its impact on fire, one of the major disturbances in the boreal forest, has probably followed a similar pattern along its entire southern fringe.

Most homesteads surrounding the southern half of the park were claimed between 1890 and 1930. This settlement cleared a mixed-wood boreal forest essentially the same as the adjacent forest within the park to the north (Fig. 3). The conversion of forest to agriculture occurred by cutting the forest, then piling and burning the debris. These debris fires frequently escaped control and burned northward into the adjacent forest (MacMillan and Gutches 1909, Mitchell 1910). Fires in the western mixed-wood boreal forest are 70% more likely to spread in a northerly direction (Fig. 8a) and these northerly spreading fires burn larger areas than fires spreading southward (Fig 8b). Thus, the influence of human-caused clearance fires started within the adjacent settlement areas extended for tens of kilometers into the forested region of the park. The increased area burned during the period of settlement offset the increase in fire cycle due to climate change (as seen in the north region). Consequently, the fire cycle of the south region of the park remained unchanged at 25 yr (CI = 15–40 yr) during the 1890–1945 period of forest conversion in the adjacent settled area.

By 1945, the majority of the agricultural region had been cleared. Fewer fires were required to burn forest debris and fewer debris fires escaped control and burned north into the forested region of the park. With settlement complete and fewer escaped human-caused fires, only those fires that started in the forest contributed to the fire frequency of the park. Thus, the possible climate-related change to a longer fire cycle observed in the north region also becomes evident in the south region of the park following the end of the settlement period.

Studies of forest fragmentation (e.g., Saunders et al. 1991) often stress how small forest fragments are influenced by large and surrounding agricultural landscapes. However, in this study we show how forest clearance and land use change primarily on one side of a forested region had an influence extending tens of kilometers into the forest. Furthermore, even lightning-caused fires would now have a reduced probability of spreading from the region south of the park due to the lack of continuous forest cover in the settled region. Thus, while fire suppression has often been proposed as an explanation for a significant increase in fire cycle reported in a number of areas, we have shown clear evidence that links a significant change in fire cycle of a large area to land use change (from forest to agriculture) in adjacent surrounding areas. Similar land use change (due to settlement) of areas surrounding other large forested areas such as the Itasca State Park (Clark 1988) and the Boundary Waters Canoe Area (Heinselman 1973) might also be responsible for reported changes in fire cycle in this century.

The spatial mosaic of size, shape, and age in the time-since-fire map can also be shown to be related to the fire frequency. As shown in the results of the spatial multivariate analysis, the mosaic in the north consists of smaller, older, more circular and compact polygons that are less similar in age but more similar in size and shape to adjacent polygons than the larger, younger, more oblong polygons with more irregular boundaries in the south that are more similar in age but less similar in size and shape to adjacent polygons. These differences in the spatial age mosaic (Figs. 10 and 11) reflect the differences in fire cycle history of the two regions. The extended period from 1795 to 1945 of a short fire cycle (25 yr) in the south would result in few remnants of past burns (seen in the north as small, old, compact and circular polygons) remaining since they would have been overburned by more recent burns. Furthermore, the subsequent change to a significantly longer fire cycle in 1945 would mean that the large burns that occurred during the settlement period in the area surrounding the south half of the Park have not themselves been overburned and therefore their size and shape would still be reflected in the polygons. The large fires in the western mixed-wood boreal forest tend to burn northward producing oblong or elliptical shapes. In contrast, the shift to a significantly longer fire cycle in 1890 in the north half of the park would be reflected in the slower disappearance of remnants of past large burns (which have been overburned by more recent burns), producing smaller, more circular, and compact polygons of older age.

The differences in time-since-fire distributions have also been linked to differences in vegetation composition. Bridge and Johnson (2000) showed that the southern half of the park has more *Populus tremuloides* and less *Picea glauca* than expected by the distribution of moisture-nutrient gradients. Weir and Johnson (1998) explained this difference between expected and observed stand composition pattern as a result of the combined impacts of logging and frequent fires. As we have shown, these frequent fires were largely due to the northward spread of debris fires set during agricultural clearing in the settlement areas surrounding the south half of the park.

Along with past fire frequency studies based on time-since-fire maps for closed canopy conifer forests (Johnson et al. 1998), we draw two general conclusions. The first is that time-since-fire distributions (and hence the fire cycles estimated from these distributions) are determined not by the more numerous small fires that take place but by infrequent large fires. This conclusion follows from the fact that the time-since-fire distribution is the cumulative distribution of area occupied by different time-since-fire dates and that it takes an extremely large number of small fires to add up to the area of a single large fire (Johnson et al. 1998). Furthermore, the frequency distributions of the area burned by fire sizes (Stocks 1991, Johnson 1992, Larsen 1997, Johnson et al. 1998) provide support for the general rule of thumb that 99% of the area burned is attributable to only 1% of the fires (Strauss et al. 1989).

The second conclusion is that, during periods (epochs) when one fire cycle is operating, the time-since-fire distribution is a negative exponential. This means that the hazard of burning is constant during this period and there are no age-related differences in fire hazard. In other words, older stands have no greater probability of burning than younger stands. Bessie and Johnson (1995) provided an explanation for this by comparing the relative roles of fuels and weather in determining fire intensity. They concluded that weather variables (and not fuel variables) accounted for most of the variation in intensity. Furthermore, as concluded by numerous studies (Stocks and Street 1983, Flannigan and Harrington 1988, Bergeron and Archambault 1993, Johnson and Wowchuk 1993, Nash and Johnson 1996), the infrequent occurrence of large wildfires is controlled by the development of persistent blocking high pressure systems. During these weather conditions, high intensity fires burn large areas and do not distinguish between stand ages or stand types. This conclusion is further corroborated by the generally elliptical or oblong shape of large wildfires in the boreal forest. If fire boundaries were influenced by stand types or ages, the shapes of large fires would reflect the irregular pattern necessitated by variation in stand types or ages.

In this paper we further show that, while the distribution of fire sizes and the negative exponential nature of the time-since-fire distribution do not change between epochs, the spatial mosaic of stand ages changes as the fire cycle changes. The fire cycle history of a region (i.e., the time-since-fire distribution) determines the general pattern of the spatial age mosaic. For example, the different spatial mosaic patterns of the north and south halves of Prince Albert National Park could be explained by the fact that the south region did not experience the climate-related change to a longer fire cycle in 1890 experienced by the north region due to the increased frequency of large, human-caused fires during the period of settlement and clearance of forest for agriculture in the surrounding area.

The mosaic pattern of stand ages that always appears in time-since-fire maps is one of smaller patches of older forest embedded within a matrix of larger patches of younger forest. No time-since-fire maps have shown the opposite pattern of small patches of younger forest embedded within a matrix of older forest. This observation can now be explained with our understanding of the link between the time-since-fire distribution and the spatial age mosaic. In order to obtain the latter pattern (implied by those who believe that old-growth forest was the norm prior to European settlement in North America), a region would have to have experienced a very long period (>200 yr) with no large fires and only small fires (i.e., a very long fire cycle). All of the time-since-fire studies of closed canopy conifer forest in North America have shown very short fire cycles prior to the end of the Little Ice Age (which occurred at the end of the 19th century). Thus, we would not expect to find this pattern of extensive old-growth forest embedded with small patches of younger forest.

In conclusion, the preoccupation of managers with determining the "natural" disturbance regime and the resulting "natural" mosaic pattern of species composition and stand ages implies a long-term equilibrium. Whether and at what spatial scales the mosaic of stand ages across a landscape may reach equilibrium under a given disturbance regime have long been questions of interest to ecologists (Watt 1947, Zackrisson 1977, Shugart and West 1981, Wu and Loucks 1995, Johnson et al. 1998). Theoretical (e.g., Turner et al. 1993, Wallin et al. 1994) and empirical studies conducted in both the boreal forest (e.g., Johnson 1979, Yarie 1981, Suffling et al. 1982, Bergeron and Archambault 1993, Larsen 1997) and other disturbance-prone landscapes (e.g. Heinselman 1973, Romme 1982, Baker 1989, Johnson and Larsen 1991) have suggested that the spatial mosaic of vegetation is unlikely to be in equilibrium with the disturbance regime. Some of the disagreement surrounding equilibrium vs. nonequilibrium can be attributed to ambiguity of definition (Wu and Loucks 1995). In this study we can provide a clear definition of equilibrium as that occurring during the periods when the fire cycle is constant. Since (a) fire cycles have been shown to change after relatively short periods or epochs of a constant fire cycle (e.g., every 50 to 100 years), (b) these epochs are often shorter than the longevity of the tree species, and (c) the spatial mosaic of stand ages is a reflection of these past fire cycles, we would conclude that the spatial mosaic of vegetation in the mixed-wood boreal forest would rarely, if ever, be in equilibrium with the disturbance regime.

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