USING TOPOGRAPHY TO MODEL AND MONITOR FIRE CYCLES IN BANFF NATIONAL PARK

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ABSTRACT

The fire management goal in Banff National Park is to maintain or restore, where possible, historical fire regimes. Fire cycles are an important component of a fire regime, and historical fire cycles provide a reference to guide the use of prescribed fire. Weather, climate, vegetation, and ignition are strongly influenced by the extremely rugged topography in the park, resulting in fire cycles that vary spatially. By analyzing a forest stand-origin database, we found that four variables (valley orientation, elevation, aspect, and proximity to the Continental Divide) explained 64% and 70% of the variation of stand-age patterns (i.e., fire cycles) in subalpine and montane ecoregions, respectively. Based on this information, historical fire cycles in Banff National Park were mapped in 50-year fire cycle classes. For each fire cycle class, the areas burned by wildfire and prescribed fires were tabulated and subtracted from the theoretical mean fire activity to determine the fire deficit (or surplus) within each of the park's land management units. These data can help managers to prioritize areas for burning and provide a method to monitor the prolonged effects of prescribed and wildfires through time.

keywords: Alberta, Banff National Park, fire cycles, fire management, prescribed fire, stand-age patterns, topography.

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INTRODUCTION

After many decades of fire suppression, managers of Canadian national parks are using planned prescribed burns to manage forest fuels, maintain wildlife habitats, and preserve fire-adapted vegetation. Studies from the Southern Canadian Rockies and Northern Rockies of the United States have shown that fire frequency varies spatially in these mountainous environments (Tande 1979, Hawkes 1980, White 1985, Barrett et al. 1991, Tymstra 1991). It has therefore been crucial for managers of Banff National Park (BNP) to understand the park-wide fire cycles in order to restore fire in a way similar to historical patterns.

Fire Cycles and Topographic Features

A *fire regime* is the type, intensity, severity, frequency, size, and pattern of fires which characterize an area, while the *fire cycle* is the number of years required to burn over an area equal to the entire area of interest (National Research Council of Canada 1987). The fire cycle integrates three fire regime components: frequency, size, and pattern. In mountainous terrain, the fire cycle varies over time and space. As described below, features of topography affect the spatial expression of fire cycles directly or indirectly in a number of ways.

Elevation

Elevation has often been identified as a controlling factor of landscape patterns (Barrows 1951, Hawkes 1980, Kushla 1996). Depending on the type of ecosystems under study, elevation can affect fire behavior in different ways. Kushla (1996) found that in the Oregon Coast Range, lower elevations favor longer fire intervals due to wetter fuels, whereas in the Canadian Rocky Mountain forests, lower elevations favor shorter fire intervals (Tande 1979) because of their drier conditions. Older stands are also more commonly found at higher elevations, even though lightning occurrence is greater than at lower elevations (Barrows 1951, Hawkes 1980). At higher elevations, fires are limited by a combination of fuel discontinuity created by treeline, patchy fuels due to poor growing conditions, and greater fuel moisture contents due to lower temperatures and fewer frost-free days. Barrows (1951) also concluded that the fire season diminished with higher-elevation zones such as the subalpine and alpine.

Aspect

Aspect is another terrain feature that affects fire cycle patterns through differential fuel drying. Generally, north-facing slopes burn less frequently than south- and west-facing slopes (Zackrisson 1977, Tande 1979, Hawkes 1980, Hemstrom and Franklin 1982, Clark 1990). This is explained by the fact that north-facing slopes receive less direct radiation and are therefore cooler and more humid. With lower evaporation, fuels are wetter and are flammable for shorter periods relative to sun-exposed aspects at the same elevation.

Distance from the Continental Divide

The location of forest stands in relation to the Continental Divide also influences fire cycles. Tymstra (1991) correlated the fire cycle to the distance from the Continental Divide for Yoho National Park, British Columbia, and determined the fire cycle was longer for areas adjacent to the Continental Divide. In Banff National Park, large areas of older forests are present along the Continental Divide, which is attributed to higher elevations, greater precipitation levels, and to a lower amount of human use and associated ignitions. Barrows (1951) arrived at similar conclusions regarding elevation zones and length of burning season for sites on the east and west sides of the Divide within Northern Rocky Mountain forests.

Valley Orientation

Valley orientation in mountainous areas is also believed to be a factor affecting the frequency of burning (Masters 1990). Small valleys perpendicular to main valleys and to prevailing winds have less chance of being burned than main valleys—the premise being that larger surface areas have more chance of being hit by lightning than small areas, and that historical and current human use, and associated human ignitions, tend to be less in small valleys than in large ones. Only two published studies have tested the influence of valley orientation on fire frequency. The results of Johnson et al. (1990) and Johnson and Larsen (1991) suggest that fire frequency was not significantly different from one valley orientation to another. However, these studies were biased by one or two large fire events that dominated their study areas, which were small in area with only two or three drainages. We therefore selected a large study area containing many valley orientations, as well as numerous examples of each type.

Hypotheses

We hypothesized that individual or combinations of major topographic elements (valley orientation, proximity to the Continental Divide, elevation, and aspect), would have a significant effect on fire cycles in BNP. A topographic stand-age model that smoothed out variations in stand-age classes and reflected long-term spatial fire patterns (fire cycles) could be used as a benchmark for restoring the appropriate frequency and extent of fire in the appropriate areas. Our research goals were therefore to 1) identify and quantify the effect of topography on stand-age patterns in order to develop a topographic fire cycle model, and 2) establish a monitoring system to track yearly burns for the purpose of restoring historical fire cycles within BNP.

STUDY AREA

During the past 2 decades, various land managers in the Canadian Rockies have carried out an extensive fire history research program. Forest stand-age information (all from fire origin) now covers a continuous landscape of about 24,000 km^2. To analyse stand-age patterns, we selected portions of that landscape with similar climate, terrain- and human-use patterns, and fire regime characteristics. The 8,100-km^2 study area was forested over 3,775 km^2. Elevations ranged between 1,500 m and 3,500 m above sea level. Treeline occurred between 2,300 m and 2,600 m above sea level. Above treeline, alpine areas composed of rock and ice accounted for over 50% of the landscape. Many valleys tend to run parallel to the Continental Divide in a northwest–southeast direction. The subalpine ecoregion was largely vegetated by coniferous trees such as lodgepole pine (*Pinus contorta*), black spruce (*Picea mariana*), Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and alpine larch (*Larix lyallii*). The subalpine fire regime was dominated by infrequent, high-intensity, stand-replacing fires (Masters 1990, Johnson and Larsen 1991, Johnson and Wowchuk 1993, Rogeau 1996). At lower elevations in the montane ecoregion, there were some stands of aspen (*Populus tremuloides*) or balsam poplar (*Populus balsamifera*), as well as lodgepole pine, white spruce (*Picea glauca*), and Douglas-fir (*Pseudotsuga menziesii*). The montane fire regime had both high-intensity and sub-lethal fire regimes, and was characterized by smaller, more frequent fires and a longer fire season than the subalpine fire regime

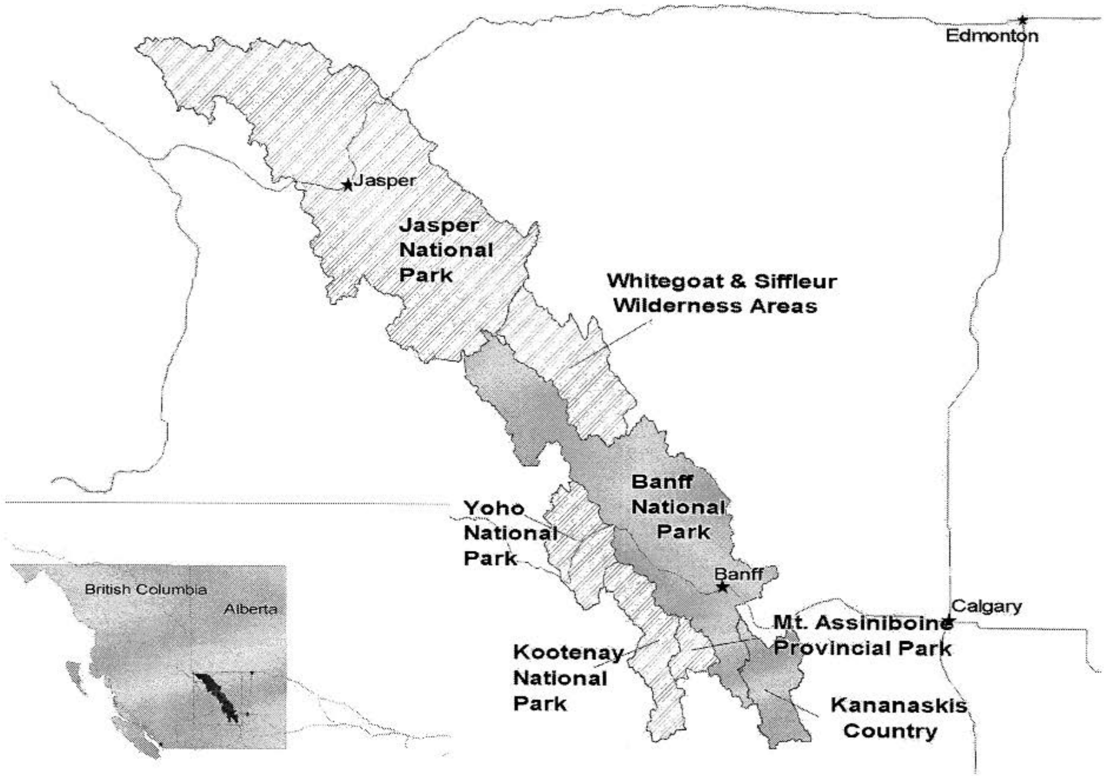

Figure 1. Study area in Banff National Park, Alberta. The shaded area corresponds to the area of study; hatched areas represent regions for which stand-origin information is available.

(White 1985). In both montane and subalpine forests, fire was the dominant natural process that shaped the vegetation. Disturbances from wind, snow avalanches, insects, tree diseases, and logging also occurred at a small scale, but these disturbed areas have also burned, or will do so eventually.

The study area (lat 116°00' N, long 51°30' W) (Figure 1) contained only the land to the east of the Continental Divide and included Banff National Park, Peter Lougheed Provincial Park, and Spray Lake and Kananaskis Valley of Kananaskis Country. Stand-origin mapping for each of these areas was completed at different times and by different researchers, but methods used for stand aging and mapping were reasonably comparable (Hawkes 1979, Johnson and Larsen 1991, Rogeau 1994, Rogeau and Gilbride 1994). In summary, the stand-origin mapping process in BNP consisted of identifying all fire boundaries from black-and-white aerial photographs taken in 1950 at a scale of 1:40,000. These boundaries were drawn onto 1:50,000 topographic maps. The sampling design consisted of sampling four trees (cross-sections) on each side of a fire boundary. Samples were sanded and aged using a dissecting microscope. Age data and fire evidence from scars and releases in tree-ring patterns were compiled and a stand-origin date was assigned to every stand identified (Rogeau and Gilbride 1994, Rogeau 1996). In the montane ecoregion, small patches of multi-aged stands were not uncommon due to sub-lethal fires. In such cases, the most prevalent age was assigned to the stand.

METHODS

Weighted Mean Forest Age

At the landscape scale, it is impossible to carry out an experiment similar to those designed in the laboratory (Hargrove and Pickering 1992). At best, one can perform a quasi-experiment (Quinn and Dunham 1983) using the range of variables found in the field. In this study, we wanted to test the effect of four topographic variables (aspect, elevation, Continental Divide, and valley orientation), and combinations of these variables, on weighted mean forest ages. Under certain conditions (a sufficiently large study area where probability of burning is random and equal across time and space), it has been theorized that the weighted mean forest age becomes a surrogate to the fire cycle (Van Wagner 1978, Johnson and Van Wagner 1985, Johnson and Gutsell 1994). Studies by Johnson et al. (1990), Masters (1990), and Johnson and Larsen (1991), who provided one fire cycle for their entire study area over a certain period of time,

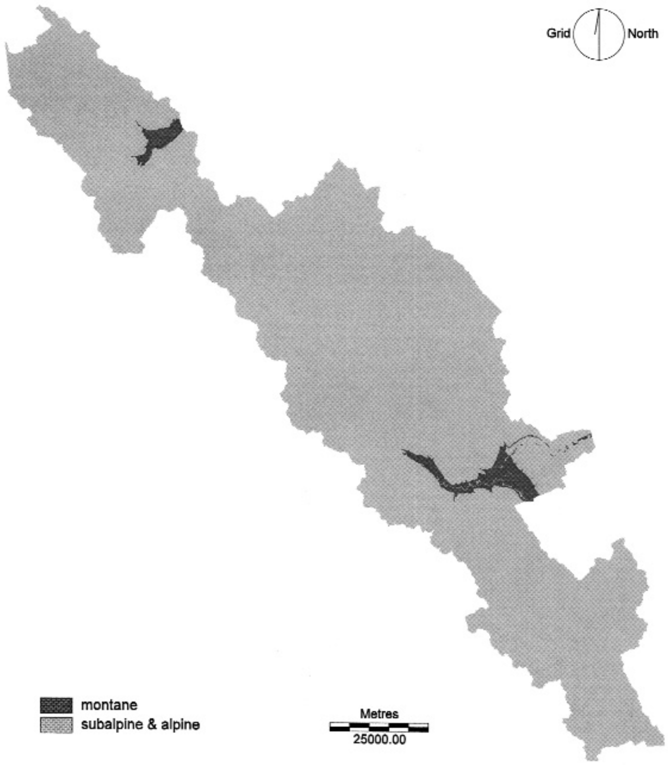

Figure 2. The landscape of Banff National Park, Alberta, divided into ecoregions representing regions under a homogeneous fire regime.

failed to meet these conditions and inappropriately substituted the weighted mean age value for a fire cycle value. In this study, rather than partitioning stand-age data over a time scale, we partitioned it on a spatial scale in order to create a series of landscape units of homogeneous fire regimes. By partitioning the study-area landscape in this fashion, our study design met the conditions and thus the weighted mean forest age was equivalent to the fire cycle. Using this method, we also obtained a series of fire cycles. For prescribed burning in mountainous terrain, this is much more appropriate than applying one fire cycle, as this could result in too much area burned in old-growth forests and too little in grasslands or in many dry coniferous and deciduous forests.

Statistical analyses (ANOVA, multiple regression) were performed using a classified Digital Elevation Model (DEM) and a 10-year age-class stand-origin map for the area, both at a scale of 1:50,000. The smallest stands drawn on the stand-origin map were about 200 m^2 (4 ha), and the pixel resolution for all map layers produced was the equivalent of 100 m^2 (1 ha). All map manipulations were performed with IDRISI GIS software (Clark Labs 1999). Statistical analyses were done with SPSS software (SPSS 1995).

Identifying Fire Regimes

We first partitioned the study area into two ecoregions— montane and subalpine—for their distinct fire regimes (Figure 2). This process was needed so that these fire regime differences would not mask the effect of topography. The montane ecoregion, which occurs at lower elevations, differs from the subalpine ecoregion in that it has broader valleys, a warmer and drier climate, different vegetation, a longer fire season, and greater human use (Janz and Storr 1977, Holland and Coen 1982, White 1985). The two fire regimes differ in the number of anthropogenic fires, season of burning, patch size, and fire patterns (White 1985, Flannigan and Wotton 1990, Rogeau 1996).

Testing for Significantly Different Mean Forest Ages

When analyzing forest fire data, it is preferable to use weighted mean ages rather than discrete fire dates because two regions can have the same set of fire dates, but the area covered by each age class will vary widely. For example, one region will have 90% of its forest dating from 1750 and only 10% dating from 1920, while the other region will have 90% of its forest dating from 1920 and 10% dating from 1750. The weighted mean forest year of origin for these two regions will be significantly different (1767 vs. 1903, respectively).

To detect broad patterns over the landscape, all topographic variables being tested were categorized *a priori*. We used the same variables in our study that are used to plan prescribed burns in BNP. ELEVATION was classified into eleven 100-m classes, ASPECT into nine 45-degree classes including flat areas, distance to the Continental Divide (DIVIDE) into thirty 1-km buffers, and valley orientation (VALLEY) was classified into 4 main valley orientations and 12 small valley orientations perpendicular to main ones. Using the cross-tabulation analysis function of the GIS, surface areas for each 10-year age class were extracted for each topographic class. This information was used to calculate the weighted mean forest age:

$$\text{weighted average age} = \sum (\text{age class} \times \text{percent area}), \quad (1)$$

where age class represents the upper bracket of the 10-year age class and where percent area represents the portion of area for that age class in relation to the total area of the landscape.

Given the number of classes per variable, 47,520 possible combinations ($11 \times 9 \times 30 \times [4 + 12]$) of topographic elements could have been created. Even though the data set was large, with so many combinations the number of topographic classes had to be reduced because there would have been too little data in each topographic class to analyze. To do this, a one-way ANOVA was performed on each topographic variable to identify whether the weighted mean forest age among topographic classes was significantly different or not. When significantly different mean forest ages were detected, means were compared using the Scheffé method ($\alpha_{0.05}$). This method is one of the most conservative (i.e., not as sensitive) and permitted the identification of larger groups (Ott 1993), thus reducing the number of topographic classes used to correlate with the distribution of forest stand ages. This analysis also provided important information as to the understanding of stand-age distribution within individual terrain components.

Quantifying the Importance of Topography on Landscape Stand-Age Patterns

We used multiple linear regression to evaluate the relative importance of the four topographic variables on weighted mean ages. We performed regression analysis with only the groups of topographic classes found to have significantly different mean forest ages. These topographic groups represented qualitative values and were treated as dummy variables. With the use of a GIS, surface areas from each age class were also obtained for each possible combination of topographic classes for the four variables tested. As above, all mean forest ages were calculated using Equation 1. These mean forest ages (in years) served as data entries for the multiple linear regression analysis. The STEPWISE method of SPSS (SPSS 1995) was used where variables were added or removed from the linear model based on probabilities of entry and removal of *F* set to 0.05 and 0.1, respectively.

Monitoring the Status of Current Fire Cycles in Banff National Park

Each year the status of fire cycles within BNP are evaluated in order to establish the fire management actions for the following year. The fire cycle status compares recent levels of fire activity to the historical fire cycle by calculating whether a surplus or deficit in area burned exists within a monitoring period. This was done for the 5 Ecological Management Areas (EMAs) and 27 Landscape Management Units (LMUs) of BNP. EMAs are the primary units for monitoring past and current rates of burning, and share similar features in terms of smoke management, human-use management, and wildlife corridor issues. LMUs are subdivisions of EMAs and are used for local planning, monitoring and management of fire, human use, and bear habitat effectiveness. Burn-area objectives for an LMU are based primarily on the fire surplus or deficits calculations described in this paper, in addition to other factors such as fire control zoning, park management plan objectives, social constraints, and ecological knowledge gaps.

The topographic fire cycle map, produced from the topographic model that we believed to represent historical fire cycle trends in BNP, was used as a benchmark to calculate burning goals and evaluate the fire cycle status across the landscape. Fire cycles were grouped into 50-year classes after being rolled back to the year 1940. This was done as BNP has been nearly devoid of wildfires during the past 60 years, a fact we attributed to effective fire prevention and suppression. The calculations were made over monitoring periods corresponding to one-third of the fire cycle. For example, in a 50-year fire cycle, the monitoring period would encompass the 17 previous years. The purpose of different monitoring periods was to ensure that during long fire cycles for example, the effects of fire during the early 1900s were considered. On the other hand, there would be little point in trying to compensate for the entire fire suppression era in areas of short fire cycles, as the entire area would require burning, thus reducing the biological diversity.

The fire cycle status (S) for year *x* was calculated using Equation 2:

$$S_{Ux} = (W + P) - \{(A/FC_U) \times [x - (FC_U/3)]\}. \qquad (2)$$

To assess the fire cycle status in each management unit, the amounts of area burned by wildfires (W) and by prescribed fires (P) during the monitoring period were combined, and the amount of area from the burning goal was subtracted from it. The burning goal for the monitoring period, expressed in hectares per year, was calculated by dividing the fire cycle area (A) by the upper end (U) of the fire cycle class (FC_U). The burning goal was then multiplied by the length of the benchmark period ($[x - (FC_U/3)]$) to determine the amount of area that would have been expected to burn during the monitoring period. To monitor the fire cycle status in the future, this calculation would be repeated on a yearly basis. The upper benchmark was chosen over the median benchmark because it was a more realistic, conservative goal for the prescribed fire program. The fire cycle status was calculated based on the burning status, which can be a negative number indicating a burned-area deficit (longer fire cycle than

Table 1. Analysis of variance results for four topographic variables of montane and subalpine ecoregions, Banff National Park, Alberta.

	Montane			Subalpine		
Source	df	*F*	*P*	df	*F*	*P*
Valley orientation	1	208.5209	<0.001	11	286.4299	<0.001
Total	19,939			357,139		
Elevation	2	1.1645	0.3123	9	328.0223	<0.001
Total	19,999			357,549		
Aspect	8	44.7131	<0.001	8	85.1323	<0.001
Total	19,999			357,679		
Continental Divide	15	36.3377	<0.001	44	47.7636	<0.001
Total	18,919			349,339		

expected), or a positive number indicating burning beyond the upper end of the historical fire cycle. For a positive fire cycle status, we suggest that the data be recalculated for the median and lower fire cycle benchmarks to assess if the fire cycle status is within the range of historical natural variation.

RESULTS AND DISCUSSION

Effects of Topography on Stand-Age Patterns

Forested areas, weighted mean forest stand-age values, and standard deviations for classes of each topographic variable are presented in Appendixes 1–4. The relationships between stand age and proximity to the Continental Divide or elevation are especially evident when plotted: Subalpine forests are older in close proximity to the Divide (Figure 3) and become increasingly older at higher elevations (Figure 4). Weighted mean forest ages from Appendixes 1–4 were used for the ANOVA, and these results (Table 1) determined that all topographic variables, with the exception of elevation for the montane ecoregion, contained at least one topographic class with a significantly different mean forest age. Scheffé's comparison of means test established new subsets of topographic classes (Table 2). Each of these new subsets was determined to have a significantly different mean forest age ($P_{0.05}$). As a general rule, the montane ecoregion had fewer subsets in each topographic variable. There are several likely explanations: 1) the smaller size of the region, which represented only 5.5% of the total landscape, did not allow for the presence of multiple valley orientations; 2) the age of the forest did not vary substantially by elevation strata and as a result, elevation was a non-contributing factor; and 3) the montane ecoregion was present only at a distance further than 10 km from the Continental Divide.

Valley Orientation

For the subalpine ecoregion, five subsets of valley orientation classes were identified. The first class, composed only of small north–south valleys running at a 45° angle to the main northwest–southeast valley direction, represented the youngest mean forest age. These valleys contained areas of recent fires (1889 to 1936) that occurred in Flints Park, Cascade, Johnson, and Bryant watersheds of BNP. All main valleys, with the exception of those running in a southwest–northeast direction, were forested by younger-aged forests as well. A fact that seemed counterintuitive was that valleys running parallel to the prevailing southwesterly winds possessed on average older-aged forests than valleys perpendicular to prevailing winds. The reason for this relates to "fire winds" rather than prevailing winds. An internal study (Baker 1984), which reviewed the synoptic situation of 10 wildland fires in BNP between 1904 and 1968, suggests that synoptic patterns associated with large fires at the time of fire ignition tend to come from the south or southeast, often followed by winds generated by cold fronts which produce northwesterly surface winds. Thus when fires occur in valleys aligned with southerly fire winds or northwesterly cold fronts, large fires often occur, resulting in younger-aged forests in these valleys.

Distance to the Continental Divide

The greatest impact of the Continental Divide on stand-age distribution occurs within the first 6 km of the Divide. This is where the mountains are the highest and where clouds persist, providing an increased amount of moisture. For the subalpine ecoregion, it was found that the forest within the first kilometer of the Divide was in fact younger than the one covering the next 6 km and also had a mean forest age comparable to those found further than 6 km away. This was

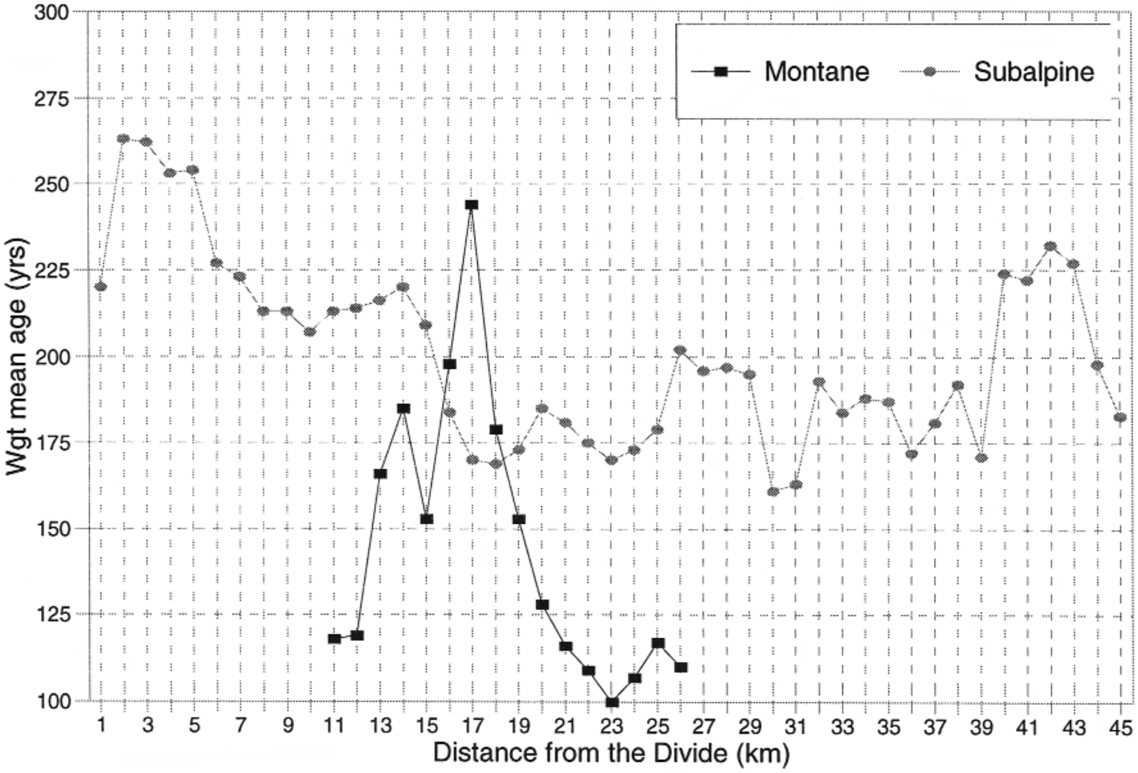

Figure 3. Weighted mean stand-age distribution by distance from the Continental Divide for the montane and subalpine ecoregions, Banff National Park, Alberta.

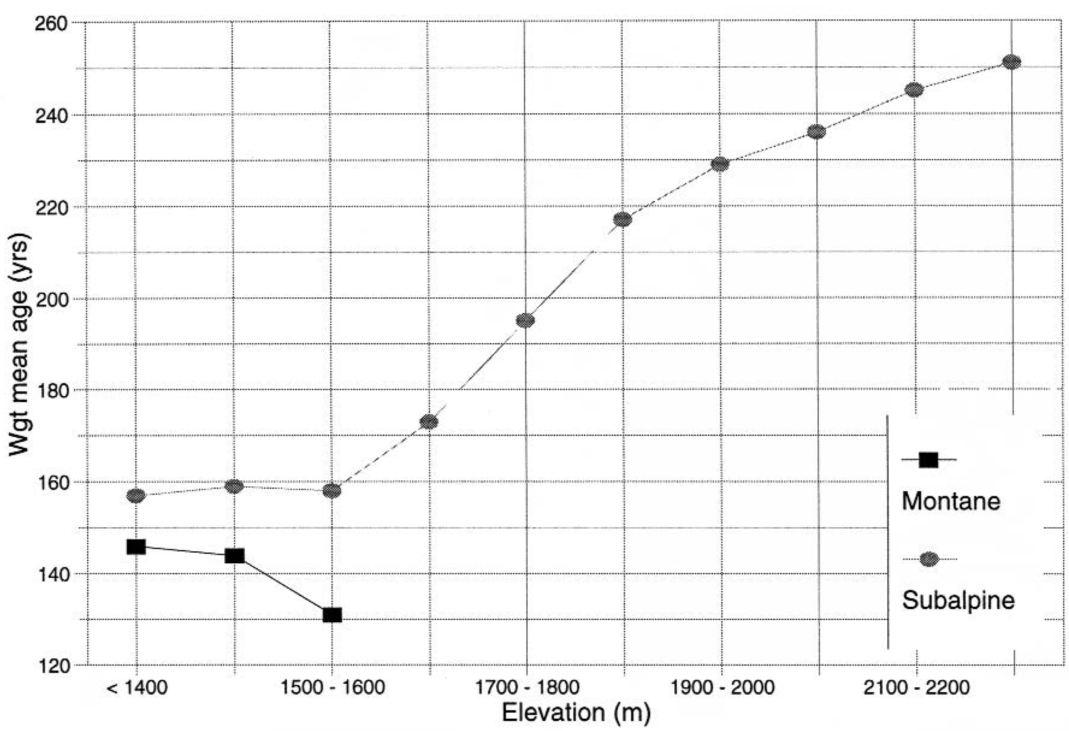

Figure 4. Weighted mean stand-age distribution by elevation for the montane and subalpine ecoregions, Banff National Park, Alberta.

Table 2. Groupings of topographic elements of similar weighted mean forest stand age in montane and subalpine ecoregions, Banff National Park, Alberta. Except for elevation in the montane ecoregion, each grouping was found to have significantly different mean forest ages from one another.

	Montane		Subalpine	
Topographic variable	Grouping	Stand age (yr)	Grouping	Stand age (yr)
Valley orientation	VO0: M1	116	VO0: S31	135
	VO1: M2	168	VO1: M1–M3–M4	182
			VO2: M2–S14–S21–S42	216
			VO3: S23–S12	252
			VO4: S41–S32	290
Continental Divide (km)	DIV0: 11–12, 20–26	114	DIV0: 2–5 km	258
	DIV1: 13–19	183	DIV1: 1, 6–15	216
			DIV2: 16–39, 44–45	185
			DIV3: 40–43	226
Aspect (degrees)	ASP0: SE–S–SW–W	122	ASP0: SW–W	184
	ASP1: NE–E–FLAT	148	ASP1: S	194
	ASP2: NW–N	215	ASP2: NE–E–SE–FLAT	206
			ASP3: NW–N	228
Elevation (m)	ELEV0: 1400–1500–1600[a]	140	ELEV0: 1400–1500–1600 m	158
			ELEV1: 1700	173
			ELEV2: 1800	195
			ELEV3: 1900	217
			ELEV4: 2000–2100	233
			ELEV5: >2100	248

[a] No significant differences.

explained by the presence of recent fires that started "upwind" in British Columbia and spread through forested passes across the Continental Divide including Howse, Kicking Horse, and Vermilion passes. Areas west of the Continental Divide have a greater density of lightning-ignited fires (Wierzchowski et al. 2002), thus creating greater burning opportunities for the low-elevation, forested mountain passes of BNP. The forest located further than 6 km away from the Divide appeared to be slightly older in the higher-elevation zones of each succeeding mountain range. However, these differences in mean forest ages were not found to be significantly different. An anomaly was located 40 km away from the Divide, in the subalpine ecoregion, where a sudden increase in mean forest age was detected in the 40–44 km zone, in the Bare and Palliser ranges. The reason for this concentration of older-aged stands is not well understood. It may be a due to a number of local factors such as ignition, wind, precipitation patterns, and chance.

Aspect

Classes of the aspect variable were comparable between the two ecoregions. Due to increased fuel moisture, north and northwest aspects were the oldest, followed by east aspects and flat lands. Younger-aged stands prevailed on the southwest and west aspects, leaving south-facing slopes to a category of their own (subalpine ecoregion only) with stand ages slightly older than the ones found on the southwest- and west-facing slopes.

Elevation

As stated earlier, elevation was found to be an insignificant predictor of mean forest age in the montane ecoregion. Due to the drier climate at lower elevations, mean ages for all three elevation strata in the montane did not vary substantially. In the subalpine ecoregion, elevation was positively related to mean ages (i.e., forest ages get older as elevation increases). This is again related to higher levels of precipitation, a shorter fire season due to the persistence of snow in the early summer, and a combination of cooler temperatures and higher relative humidity found at high altitude.

Reclassification of Variables and Topographic Models

As a result of the analysis of variance, the four variables for the subalpine ecoregion were reclassified as

Table 3. Multiple R and R^2 values obtained from the multiple linear regression analysis of four topographic variables in montane and subalpine ecoregions, Banff National Park, Alberta. For the montane ecoregion database, variables had to be entered as a group.

Ecoregion	Variable[a]	Multiple R	R^2
Montane	VO1 + DIV1 + ASP1 + ASP2	0.83725	0.70100
Subalpine	DIV2	0.46262	0.21402
	VO0	0.56597	0.32033
	VO1	0.66239	0.43877
	ELEV5	0.70775	0.50091
	VO2	0.73665	0.54265
	ELEV4	0.76283	0.58191
	DIV3	0.78456	0.61554
	ELEV0	0.79341	0.62949
	ASP3	0.79921	0.63873
	ASP2	0.80157	0.64252

[a] Aspect (ASP), proximity to the Continental Divide (DIV), elevation (ELEV), and valley orientation (VO). See text and Appendixes 1–4 for further details on these variables.

follows (Table 2): 4 VALLEY classes, 4 DIVIDE classes, 4 ASPECT classes and 6 ELEVATION classes. Out of this total of 480 possible combinations of topographic elements, 86 simply did not exist on the landscape or were not forested. As well, 108 out of these 394 combinations were represented by less than 100 ha and sometimes by only a few hectares, so they were also removed from the analysis. This was done because these combinations would have lowered the degrees of freedom for information that was too weak to be representative. In the end, weighted mean forest ages (Equation 1) were calculated for 286 regions of distinct topographic elements. For the montane ecoregion (Table 2), the lower number of topographic classes identified resulted in the combination of only 12 topographic elements (2 VALLEY classes × 2 DIVIDE classes × 3 ASPECT classes).

The last and most important step of the analysis was to determine which topographic components best explain stand-age patterns (hence fire cycles) in the study area. Results of the multiple linear regression analysis (Table 3) strongly indicated that aspect, distance to the Continental Divide, and valley orientation have a strong positive correlation (R^2 = 84%) with stand ages in the montane ecoregion. These topographic elements account for 70% of stand-age patterns in this landscape. Similarly, in the subalpine ecoregion, valley orientation, elevation, distance to the Continental Divide, and aspect show a strong correlation (R^2 = 80%) with stand ages, and these topographic elements account for 64% of stand-age patterns. While the stepwise regression was used for the subalpine ecoregion, it was not used for the montane ecoregion because the probability of entry of F, set to 0.05, had been reached. This implies that no separate variable can explain the stand-age patterns in the montane ecoregion. This could be due to the reduced amount of area and topographic classes in the montane ecoregion. However, the interaction among variables was strong enough to produce a significant model (all the variables were entered at once). As a result, it was not possible to quantify the importance of each variable, but it is likely that the same variables had comparable impact in both the montane and the subalpine ecoregions.

In the subalpine ecoregion, most of the classes of valley orientation, classes of close proximity to the Continental Divide, and classes of higher elevation displayed significant correlations to mean ages. Table 3 shows, in order of importance, the topographic classes that were entered into both the montane and subalpine regression models. For the subalpine ecoregion, proximity to the Continental Divide, specifically the 1-km and 6- to 15-km zones, followed by small north–south valleys running perpendicular to northwest–southeast valleys, had the greatest effect on stand-age patterns. In the montane ecoregion, northwest- and north-facing slopes, followed closely by all valley orientations and proximity to the Divide classes, had the most influence on stand-age patterns. In the subalpine ecoregion, aspect was the least important variable and only slightly increased the strength of the topographic model. The topographic linear models are formulated as follows for the montane and subalpine ecoregions:

Montane Mean Age = 1908.43 – 14.75(ASP1) – 64.38(ASP2) – 53.60(DIV1) – 36.75(VO1).

Subalpine Mean Age = 1719.07 – 11.91(ASP2) – 21.58(ASP3) + 71.42(DIV2) + 42.57(DIV3) + 28.25(ELEV0) – 37.84(ELEV4) – 55.87(ELEV5) + 135.50(VO0) + 77.23(VO1) + 35.81(VO2).

Fire Cycle Status

The strong relationship of terrain with stand-age distribution detected in our study demonstrates that the topographic stand-age (i.e., fire cycle) model provides a useful fire management tool. Figure 5 represents the benchmark fire cycle map that was used to calculate the fire cycle status of each LMU in BNP. As an example, burning goals and resulting fire cycle status for each fire cycle class of the Panther LMU are calculated in Table 4. Despite repeated planned ignitions in the last 15 years, this LMU is still running a fire deficit at all levels of the fire cycle, resulting in much longer fire cycles than targeted for. This is true for all LMUs in the park and indicates the need for a much more active prescribed fire program.

Future Research

Although our analysis was limited to four components of the physical landscape, the complex interaction between terrain and other processes should not be ignored. Spatial variation in fire cycles over the landscape reflects both the heterogeneity of terrain features and the way topography influences various processes such as aboriginal activity, human settlement and current use, and wind and climatic patterns. Further research is necessary to assess the influence of historical and current human land use, as well as climatic patterns on fire distribution.

Similar research is also needed in other areas affected by terrain irregularities and for which the fire regime is known to be different from that of the east side of the Continental Divide. Different divisions of the landscape, as well as the testing of different topographic parameters, could also be attempted to complement the current results. In our study, the division of the landscape into ecoregions was debatable because the small area of the montane ecoregion limited our sample size.

Another tool that can serve as a guideline for dividing the landscape is a map of precipitation regime patterns. This may better represent homogeneous regions of fire regime on the landscape, since broad-scale precipitation patterns appear to be related to general Drought Code values (a numerical rating of the fuel moisture content of the deep compacted organic matter). Although Fine Fuel Moisture Codes (Stocks et al. 1989), in combination with wind, are more influential on fire ignition and spread, high Drought Code values in the mountains tend to be associated with the occurrence of larger stand-replacing fires (Baker 1984).

In the context of future research, we suggest that fetch—the distance along open land over which the wind blows—is a topographic parameter that should not be ignored. Based on our database, there is strong evidence that the likelihood of a stand burning increases with increasing distance from valley headwaters. This is a parameter that can replace the distance to the Continental Divide parameter and that can also incorporate the valley orientation parameter in its classification. By testing with only fetch, elevation, and aspect, the number of topographic combinations would be greatly reduced and hence, the sampling area within each combination would be increased.

CONCLUSIONS

In this study we partitioned the landscape of BNP into areas of homogeneous fire regime conditions based on similar weighted mean forest stand ages. As the weighted mean stand age is equivalent to the fire cycle under such conditions, we were able to show that the fire cycle varies spatially in mountainous terrain, contrary to the findings of studies on similar landscapes in the Canadian Rockies (Johnson et al. 1990, Masters 1990, Johnson and Larsen 1991). The difference in the outcome of these studies is likely due to the large size of our study area, which was much greater than the largest fires of the region and included many valleys rather than being restricted to one or a few valleys.

The ability to predict and map long-term fire cycle patterns utilizing topographic variables is important to managers who use prescribed fire for ecological restoration in mountainous landscapes. Within Canadian national parks, vegetation management plans that describe normal landscape-age patterns and deviations beyond the range of natural variability are required. Therefore, it is important to recognize that spatial variation in fire cycles does exist, and that these patterns should be maintained through the appropriate use of prescribed fire. This study increased our understanding of fire cycle patterns in Banff National Park by analyzing the distribution of forest stand ages across a large landscape. Our analysis showed that a topogra-

Table 4. Burning goals (hectares per monitoring period), area burned (hectares) by wildfires and prescribed fires, fire cycle status in 2000 expressed in burned-area deficit or surplus (hectares) and current fire cycle, Panther Land Management Unit, Banff National Park, Alberta. Burning goals were calculated for the upper end of each 50-year fire cycle class. To assess the fire cycle status, the amounts of area burned by wildfires (W) and by prescribed fires (P) during the monitoring period were combined, and the amount of area from the burning goal was subtracted from it. The burning goal for the monitoring period, expressed in hectares per year, was calculated by dividing the fire cycle area (A) by the fire cycle class (FC). The burning goal was then multiplied by the length of the benchmark period (MP) to determine the amount of area that would have been expected to burn during the monitoring period.

			Monitoring period					Fire cycle status in 2000 (W + P) – {[A/FC] × MP}	
Fire cycle (FC)	Area (A)	Area per year (A/FC)	Start year	Number of years (MP)	Burning goal (A/FC) × MP	Wildfires (W)	Prescribed fires (P)	Burn area deficit	Current fire cycle
1–50	0	0	1983	17	0	0	0	0	n/a
51–100	1229	12.29	1967	33	406	12	65	–329	526
101–150	8756	58.37	1950	50	2919	0	1544	–1375	284
151–200	7328	36.64	1933	67	2455	0	999	–1456	492
201–250	2874	11.5	1917	83	955	0	345	–610	691
251–300	24	0.08	1900	100	8	0	3	–5	800

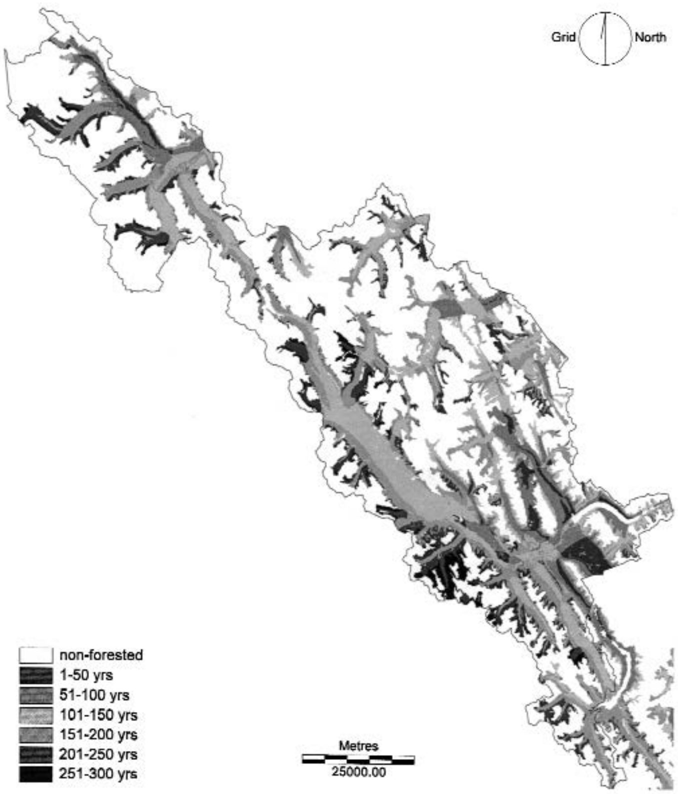

Figure 5. Topographic fire cycle map, Banff National Park, Alberta, produced from a topographic stand-age model and rolled back to 1940 because the park has been nearly devoid of wildfires during the past 60 years.

phy model can be a useful predictor of meso-scale fire cycle patterns. Using the information provided by this study, park managers can ensure that prescribed fires can be managed to maintain or restore the long-term pattern of fire cycles.

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LITERATURE CITED

Baker, K.A. 1984. Weather patterns and wildland fire in Banff National Park. Technical report prepared for Banff National Park, Banff, AB.

Barrett, S.W., S.F. Arno, and C.H. Key. 1991. Fire regimes of western larch–lodgepole pine forests in Glacier National Park, Montana. Canadian Journal of Forest Research 21:1711–1720.

Barrows, J.S. 1951. Fire behavior in Northern Rocky Mountain forests. Station Paper No. 29, U.S. Department of Agriculture, Forest Service, Northern Rocky Mountain Forest and Range Experiment Station, Missoula, MT.

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

Clark Labs. 1999. IDRISI for Windows. Version 3.2. Clark Labs for Cartographic Technology and Geographic Analysis, Clark University, Worcester, MA.

Flannigan, M.D., and B.M. Wotton. 1990. Lightning-ignited forest fires in northwestern Ontario. Canadian Journal of Forest Research 21:277–287.

Hargrove, W.W., and J. Pickering. 1992. Pseudoreplication: a sine qua non for regional ecology. Landscape Ecology 6:251–258.

Hawkes, B.C. 1979. Fire history and fuel appraisal study of Kananaskis Provincial Park, Alberta. M.Sc. Thesis, University of Alberta, Edmonton.

Hawkes, B.C. 1980. Fire history of Kananaskis Provincial Park—mean fire return intervals. Pages 42–45 *in* M.A. Stokes and J.H. Dieterich (technical editors). Proceedings of the Fire History Workshop. General Technical Report RM-81, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Tucson, AZ.

Hemstrom, M.A., and J.F. Franklin. 1982. Fire and other disturbances of the forest in Mount Rainier National Park. Quaternary Research 18:32–51.

Holland, W.D., and G.M. Coen. 1982. Ecological land classification of Banff and Jasper National Parks, Alberta. Volumes 1, 2, and 3. Publication M-83-2, Alberta Institute of Pedology, Edmonton.

Janz, B., and D. Storr. 1977. The climate of the contiguous mountain parks. Project Report No. 30, Atmospheric Environment Services, Toronto, ON.

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

Johnson, E.A., and S.L. Gutsell. 1994. Fire frequency models, methods and interpretations. Advances in Ecological Research 25:239–283.

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

Johnson, E.A., and C.E. Van Wagner. 1985. The theory and use of two fire history models. Canadian Journal of Forest Research 15:214220.

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

Kushla, J.D. 1996. Analyzing fire mosaics in temperate coniferous forest with GIS and remote sensing. Ph.D. Dissertation, Oregon State University, Corvallis.

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

National Research Council of Canada. 1987. Glossary of forest fire management terms. Fourth edition. Publication NRCC No. 26516, Canadian Committee on Forest Fire Management, Ottawa, ON.

Ott, L.R. 1993. An introduction to statistical methods and data analysis. Fourth edition. Wadsworth, Belmont, CA.

Quinn, J.F., and A.E. Dunham. 1983. On hypothesis testing in ecology and evolution. American Naturalist 122:602–617.

Rogeau, M.-P. 1994. Fire history study of the Spray Lakes Area, Alberta. Technical Report for the Central Rockies Ecosystem Interagency Liaison Group, Banff National Park, Banff, AB.

Rogeau, M.-P. 1996. Understanding age-class distributions in the Southern Canadian Rockies. M.Sc. Thesis, University of Alberta, Edmonton.

Rogeau, M.-P., and D. Gilbride. 1994. Forest stand origin mapping of Banff National Park, Alberta. Resource Conservation Branch, Banff National Park, Banff, AB.

SPSS. 1995. SPSS for Windows. Version. 6.1. SPSS, Inc., Chicago, IL.

Stocks, B.J., B.D. Lawson, M.E. Alexander, C.E. Van Wagner , R.S. McAlpine, T.J. Lynham, and D.E. Dubé. 1989. The Canadian Forest Fire Danger Rating System: an overview. Forestry Chronicle 65:258–265.

Tande, G.F. 1979. Fire history and vegetation patterns of coniferous forests in Jasper National Park, Alberta. Canadian Journal of Botany 57:1912–1931.

Tymstra, C. 1991. Fire history of Yoho National Park, British Columbia and implications for fire management. M.Sc. Thesis, University of Alberta, Edmonton.

Van Wagner, C.E. 1978. Age-class distribution and the forest fire cycle. Canadian Journal of Forest Research 8:220–227.

White, C. 1985. Wildland fires in Banff National Park, 1880–1980. Occasional Paper No. 3, National Parks Branch, Parks Canada, Environment Canada. Banff National Park, Banff, AB.

Wierzchowski, J.L., M. Heathcott, and M.D. Flannigan. 2002. Lightning and lightning fire, Central Cordillera, Canada. International Journal of Wildland Fire 11:41–51.

Zackrisson, O. 1977. Influence of forest fires on the North Swedish boreal forest. Oikos 29:22–32.

Appendix 1. Area, weighted mean forest stand age, and standard deviation for valley orientation classes in montane and subalpine ecoregions, Banff National Park, Alberta. ⊥ = perpendicular.

		Montane			Subalpine		
			Stand age (yr)			Stand age (yr)	
Valley [a,b]	Orientation	Area (ha)	Mean	SD	Area (ha)	Mean	SD
M1	NW/SE	8,680	116	35	175,160	182	105
M2	NE/SW	11,260	168	102	70,960	219	118
M3	N/S				6,590	181	101
M4	E/W				13,910	183	120
S12	S-NW/SE ⊥ M-NE/SW				29,100	262	115
S14	S-NW/SE ⊥ M-E/W				3,050	206	119
S21	S-NE/SW ⊥ M-NW/SE				27,970	217	120
S23	S-NE/SW ⊥ M-N/S				1,010	242	120
S31	S-N/S ⊥ M-NW/SE				7,120	135	112
S32	S-N/S ⊥ M-NE/SW				8,020	296	91
S41	S-E/W ⊥ M-NW/SE				10,760	284	108
S42	S-E/W ⊥ M-NE/SW				3,490	220	84
Total		19,940	145	84	357,140	204	115

[a] M: main valleys, S: small valleys perpendicular to main ones.
[b] 1: NW/SE direction, 2: NE/SW direction, 3: N/S direction, 4: E/W direction.

Appendix 2. Area, weighted mean stand age, and standard deviation for distance classes from the Continental Divide in montane and subalpine ecoregions, Banff National Park, Alberta.

	Montane			Subalpine		
		Stand age (yr)			Stand age (yr)	
Distance (km)	Area (ha)	Mean	SD	Area (ha)	Mean	SD
0–1				5,110	220	131
1–2				8,810	263	137
2–3				10,320	262	127
3–4				11,490	253	115
4–5				13,480	254	116
5–6				15,380	227	117
6–7				14,840	223	109
7–8				14,100	213	105
8–9				13,550	213	105
9–10				13,030	207	106
10–11	570	118	22	12,500	213	106
11–12	800	119	48	11,800	214	108
12–13	1,140	166	97	10,870	216	117
13–14	1,360	185	103	9,580	220	123
14–15	1,140	153	90	10,740	209	115
15–16	1,030	198	113	12,380	184	110
16–17	1,150	244	108	13,940	170	99
17–18	1,490	179	108	11,470	169	93
18–19	1,380	153	88	9,870	173	104
19–20	1,410	128	74	8,280	185	130
20–21	880	116	42	6,190	181	134
21–22	1,160	109	24	5,420	175	121
22–23	1,270	100	12	5,470	170	108
23–24	1,370	107	17	5,060	173	108
24–25	1,420	117	24	4,560	179	126
25–26	1,350	110	33	5,520	202	130
26–27				6,450	196	120
27–28				6,010	197	124
28–29				6,360	195	117
29–30				6,160	161	98
30–31				5,730	163	95
31–32				5,900	193	106
32–33				6,020	184	100
33–34				4,890	188	101
34–35				4,060	187	92
35–36				4,720	172	83
36–37				4,480	181	89
37–38				3,640	192	94
38–39				3,170	171	90
39–40				3,490	224	116
40–41				2,540	222	117
41–42				2,610	232	116
42–43				3,280	227	132
43–44				3,300	198	118
44–45				2,770	183	105
Total	18,920	145	84	349,340	201	115

Appendix 3. Area, weighted mean stand age, and standard deviation for aspect classes in montane and subalpine ecoregions, Banff National Park, Alberta.

	Montane			Subalpine		
		Stand age (yr)			Stand age (yr)	
Aspect (degrees)	Area (ha)	Mean	SD	Area (ha)	Mean	SD
0–45 (NE)	1,610	145	86	47,000	212	116
45–90 (E)	1,300	140	87	63,670	204	113
90–135 (SE)	1,370	121	71	37,440	205	118
135–180 (S)	2,880	124	72	30,890	194	110
180–225 (SW)	3,260	123	52	34,150	182	104
225–270 (W)	3,060	118	50	61,230	186	109
270–315 (NW)	1,470	218	110	38,980	224	121
315–360 (N)	1,490	211	103	35,920	232	122
Flat	3,560	159	83	8,400	204	117
Total	20,000	145	83	357,680	204	115

Appendix 4. Area, weighted mean stand age, and standard deviation for elevation classes in montane and subalpine ecoregions, Banff National Park, Alberta.

	Montane			Subalpine		
		Stand age (yr)			Stand age (yr)	
Elevation (m)	Area (ha)	Mean	SD	Area (ha)	Mean	SD
<1400	16,140	146	82	14,370	157	91
1400–1500	3,080	144	90	24,020	159	89
1500–1600	780	131	83	33,520	158	89
1600–1700				44,400	173	99
1700–1800				50,710	195	104
1800–1900				53,200	217	118
1900–2000				50,640	229	124
2000–2100				44,680	236	124
2100–2200				28,820	245	123
>2200				13,190	251	122
Total	20,000	145	84	357,550	204	115