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Author(s): E. A. Johnson, K. Miyanishi, J. M. H. Weir
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Wildfires in the western Canadian boreal forest: Landscape patterns and ecosystem management

Johnson, E.A.1, Miyanishi, K.2* & Weir, J.M.H.3

1Department of Biological Sciences and Kananaskis Field Stations, University of Calgary, Calgary, Alberta, Canada T2N 1N4; 2Department of Geography, University of Guelph, Guelph, Ontario, Canada N1G 2W1; 3Prince Albert National Park, Waskesiu Lake, Saskatchewan, Canada SOJ 2YO; *Corresponding author; Fax +1 519 837 2940; E-mail kmiyanis@uoguelph.ca

Abstract. Mimicking of natural disturbance for ecosystem management requires an understanding of the disturbance processes and the resulting landscape patterns. Since fire is the major disturbance in the boreal forest, three widely held beliefs about fire behavior and resulting landscape patterns are examined in light of the empirical evidence available. These beliefs are: (1) that there is a 'natural' fire frequency for boreal ecosystems; (2) that the landscape mosaic created by wildfire is generally one of small, younger patches embedded within a matrix of older forest; and (3) that forest flammability is largely controlled by fuel accumulation. Despite the apparently logical basis for such beliefs, they are not well supported by empirical evidence. This discrepancy is explained by problems such as failure to appreciate the relationship between number of fires and area burned and inappropriate extrapolations or generalizations from other regions and vegetation types. The most important implications for management are that the natural disturbance processes producing landscape patterns in the boreal forest generally operate at much larger scales than management units, and that humans may have more indirect (through landuse change) rather than direct (through fire suppression) effects on the frequency of wildfires.

Keywords: Fire cycle; Forest fire; Fuel accumulation; Landscape ecology; Landscape mosaic; Forest management.

Introduction

Over the last 25 years, it has been proposed on many occasions that forests should be managed for their total ecosystem and not just for certain parts, e.g. timber, water, or large game animals (Franklin et al. 1986; Hunter 1990). However, our present state of knowledge about most ecosystems makes this goal difficult. Thus, as a temporary measure, the idea of imitating certain ecological processes to create 'natural' ecosystem patterns has been suggested as a more holistic approach to forest management. Disturbance has been recognized as playing a key role in creating the composition and age patterns observed in forested ecosystems (White 1979). Since timber harvesting is one of the important uses of forested ecosystems, it has been suggested that harvesting should imitate natural disturbances (Hunter 1993; Hansen et al. 1991; Runkle 1991; Anon. 1993; Galindo-Leal & Bunnell 1995). Furthermore, since forest fires are one of the predominant disturbances in the boreal and boreal montane forests, it follows that timber harvesting could attempt to imitate forest fires in certain ways (Hunter 1993; Anon. 1994; Bergeron & Harvey 1997). Also, if the natural fire frequency of a forest reserve has been reduced by human intervention, prescribed fires could be used to try to produce the landscape patterns previously maintained by wildfire (e.g. Lopoukhine & White 1985, but see Weir et al. 1995). This approach of attempting to mimic the effects of natural disturbance on the landscape requires an adequate understanding of the disturbance process and the resulting pattern.

Over the years, a series of beliefs has developed about how forest fires in the western boreal forest create patterns in the vegetation. These beliefs are widespread not only with the lay public but also among industry-affiliated foresters and thus have an impact on forest management in North America. In this paper we will examine three of these beliefs, the probable basis for them, and their validity based on the empirical evidence. To some degree, these beliefs may have arisen from studies which looked at local scale patterns and their explanations. Here we attempt to address landscape level patterns and the large scale processes that generate these patterns. Each of these beliefs has clear implications for the kind of pattern forestry and wilderness management would attempt to mimic in their harvesting and prescribed burning; these management implications are addressed in the final section of this paper.

There is a 'natural' fire frequency for boreal forest ecosystems

Fire frequency has been studied now for more than 25 years (see Johnson & Gutsell 1994). From these studies, we have developed a fair understanding of the theory,
methodology and analysis required to obtain a reasonably accurate and precise estimate of the time-since-fire distribution which is used to estimate fire frequency. Time-since-fire distributions are determined from time-since-fire maps (Johnson & Van Wagner 1985) which consist of a collection of spatially disjunct areas, each of which is identified by the time since it last burned.

The time-since-fire distribution (which is a cumulative distribution) gives the proportion of the study area that has survived without a fire up to time $t$. Population ecologists will recognize this as a survivorship curve but with area of land replacing individuals. The time-since-fire map gives survivorship since it shows the rate of disappearance of burns as they are successively overburned by more recent fires.

The time-since-fire distribution has been found to fit best a negative exponential or Weibull distribution (Johnson & Van Wagner 1985) and can thus be plotted as a straight line on semilog or Weibull paper. The parameter(s) of the distribution describe the fire frequency or its inverse, the fire cycle. The fire cycle is a cycle only in the sense that the study area has gone through a time period in which an area equivalent to the study area has burned. Any changes or differences in fire cycle will be indicated by abrupt changes in the slope of the distribution. They can be caused by spatial differences in fire cycle (i.e. different parts of the study area having different fire cycles) or temporal changes in fire cycle (i.e. changes in fire cycle at some time in the past). Any changes or differences in slope must be shown to be statistically significant.

The detection of these changes in the fire cycle will depend on the nature of the data collected (the scale of the resolution and the definition of time-since-fire as discussed previously). For example, it will not be possible to use the distribution to detect spatial differences in fire cycle if these differences occur at a finer scale than the resolution of the time-since-fire map. Also, if the time-since-fire map was constructed using only time since the last crown fire, the resulting distribution will not detect surface fires. Choice of the breakpoints based on independent data and significance tests of differences in the parameters are required to validate the existence of changes in slope (Reed et al. 1998).

The evidence from studies using time-since-fire maps in the western boreal, boreal montane and near-boreal forest (e.g. Heinselman 1973; Yarie 1981; Suffling et al. 1982; Masters 1990; Bergeron 1991; Johnson & Larsen 1991; Weir 1996) give the following general conclusions. The boreal forest burns over fairly frequently, so that virtually all areas will have burned within 300 to 400 years. Thus, the possibilities for old-growth forests are limited and, in fact, rarely more than 5 to 10 % of a landscape will be older than 200 years (Johnson et al. 1995).

In general, these fire frequency studies have found one or two major temporal changes in the fire cycle (e.g. Fig. 1). One change occurred in the early to mid-1700s and another between the end of the 1800s and early 1900s. Both changes appear to be correlated to a large-scale change in climate associated with the Little Ice Age (Bergeron & Archambault 1993).

In addition, fire frequency changes have been documented for fragmented forests resulting from landuse change. For example, Weir & Johnson (1998) found changes in fire frequency of their boreal forest study area in central Saskatchewan resulting from the removal of continuous forest cover in an adjacent area from which fires had previously spread. This phenomenon is particularly obvious in areas where agricultural settlement has occurred adjacent to forested areas. This indirect anthropogenic reduction in fire frequency can be mistakenly attributed to fire suppression.

The conclusion we can draw from these fire frequency studies is that fire cycles have changed more than once in the past 200 - 300 yr in the boreal forest. Thus, as noted for other ecosystems as well (Sprugel 1991), there is no single 'natural' fire cycle for any part of the boreal forest. Instead, the forested landscape mosaic is a reflection of a dynamic fire cycle and carries in it the memory of different past fire cycles.

The landscape mosaic created by wildfire is generally one of small, younger patches embedded within a matrix of older forest

This second belief possibly arises subconsciously from the juxtaposition of two facts: (1) the landscape of
the boreal forest is clearly a mosaic of stands of different ages resulting from wildfires (Johnson 1992); and (2) small fires occur much more frequently than large fires (e.g. Fig. 2a). Thus, it might appear self-evident that, since small fires are much more frequent than large fires, we should expect to see numerous, recently burned, small areas embedded within large patches of older forest originating from past infrequent large fires (Fig. 3a). This view of the landscape has probably formed part of the basis for some environmental groups advocating small clearcuts to mimic these numerous small fires or disturbance gaps.

However, it is important to note that what Fig. 2a shows is the number of fires in each size class, not the area burned by fires in each size class. The limitation of viewing this size frequency distribution as a creator of the landscape age-mosaic is apparent by considering how many small (1 ha) fires are needed to equal the area in one large (10,000 ha) fire.
More appropriate for a landscape pattern viewpoint is a graph which shows the distribution of the *area burned* by fires of different size classes. Fig. 2b is such a graph and uses the same data as in Fig. 2a. Clearly, in the boreal forest of central Saskatchewan, the large fires account for the vast majority of the total area burned and small fires (< 100 ha) account for less than 1% of the area burned (see also Stocks 1991; Johnson 1992). Strauss et al. (1989) used a similar analysis to show that ca. 99% of the area burned in chaparral vegetation in southern California and Mexico is attributable to 1% of the fires.

Thus, despite their numbers, small fires play a relatively unimportant role in determining the landscape age mosaic since they constitute such a small proportion of the landscape and are spatially rare occurrences. We should therefore expect landscapes created by wildfire to be determined by the few large fires, both recent and those that occurred in the past. Furthermore, since older burns would be subsequently overburned, we should expect a landscape mosaic pattern consisting of large areas of younger forest resulting from the most recent large fire(s) interspersed with small patches of older forest which are remnants of past large fires.

Simply looking at a large (covering thousands of km²) time-since-fire map for any part of the boreal and boreal montane forest would quickly confirm this pattern (e.g. Fig. 3b). It is important to note the distinction between time-since-fire maps which record only the most recent fire for each polygon and maps which record polygons with multiple fire dates (e.g. Tande 1979). Unfortunately, time-since-fire maps for large areas are rare, although those for small areas (1000 ha or less) are relatively common. Time-since-fire maps used in studies by Heinselman (1973), Johnson (1979), Yarie (1981), Masters (1990), Johnson & Larsen (1991), Bergeron (1991), Dansereau & Bergeron (1993), and Weir (1996) show that the landscape mosaic is, in fact, made up of large areas of younger forest and small patches or polygons of older forest. The large polygons tend to be oblong while the small polygons tend to be more circular. Also, the large polygons of younger forest are often adjacent to each other while the small polygons of older forest are embedded within these large polygons. This general mosaic pattern provides further evidence that the landscape pattern of the western Canadian boreal forest is the result of a few recent large fires, within which remain small patches of older, large burns that have been progressively overburned. Small fires play little role in determining the landscape age-mosaic simply because they occupy such a minor proportion of the total area.

*Forest flammability is largely controlled by fuel accumulation in the western boreal forest*

Another common belief is that, as conifer forests age, fuels accumulate and the increased fuel load leads to increased flammability of the forests (Brown 1983; Van Wagner 1983; Barrett et al. 1991; Agee 1993; Arno et al. 1993). What is generally meant by flammability among ecologists and foresters is fire intensity (kW/m), the heat output from the flaming front of fires (Alexander 1982).

While it is true that fire intensity is influenced by fuel variables (fuel load, fuel depth, mass density, heat of combustion, and surface-to-volume ratio), it is also controlled by weather variables (fuel moisture content and wind speed) (Bessie & Johnson 1995). In the past, most studies addressing the role of fuel variables in fire behavior have held the weather conditions constant and only allowed the fuel variables to vary (e.g. Agee & Huff 1987; Keane et al. 1990). Not surprisingly, these studies found that fire intensity varied with variation in the fuel variables. However, if the weather variables are not held constant but are also allowed to vary along with the fuel variables, these two groups of variables can be compared for their relative importance in determining fire intensity. Bessie & Johnson (1995) used empirical fuel values from 47 montane boreal conifer stands varying in age from 22 to 258 yr and 35 yr of daily weather data during the fire season to compare the relative importance of fuel and weather variables. They used Rothermel’s (1972) model of fire intensity for surface spreading fires and Van Wagner’s (1977) model of fire intensity for crown fire initiation. These models were chosen because they are the most widely used models of fire intensity in North America for fire behavior prediction and are incorporated into the Canadian and American Fire Weather Behavior Systems. Bessie & Johnson’s study showed that the weather variables were much more important than fuel variables in determining fire intensity.

One explanation given for this result is that weather variables show much greater variation than fuel variables. For example, over the course of hours and days, fuel moisture ranged from 5-100%, and wind speed ranged from 0-100 km/h. On the other hand, the fine and medium size fuels (which are the principal contributors to frontal fire intensity) varied only from 0.5 to 4 kg/m² and were found to be stable over long periods of time. Large boles which contribute much biomass, particularly in older forests, play a relatively insignificant role in flaming combustion (i.e. the spread of fire). Since weather variables were found to vary over several orders of magnitude while the fuel variables varied over a much smaller range of values, variation in fire intensity (and flammability) would be due...
more to variation in weather than in fuels.

Furthermore, the crown fire initiation model predicted that fire intensity would be greater during years with large area burned compared to small area burned years (Bessie & Johnson 1995). The weather variables in these large area burned years were shifted towards extreme values. During these very dry weather conditions, the relative importance of fuels diminished since all stands, regardless of their fuel load, achieved the threshold required for crown fires to develop. Consequently, fire intensity in the boreal forest is primarily determined by variation in weather among years rather than by fuel variation associated with either stand type or stand age. Note that this study did not include trees with highly elevated crowns such as white or red pine nor any significant deciduous component that could also have an effect on crown fire initiation (Johnson 1992). The extreme weather conditions associated with large fires in these forests may also help to explain why the changes in fire cycle found in the fire frequency studies were related to large scale climatic changes and not to small scale spatial differences in topography or vegetation type.

While the surface fire model (Rothermel 1972) and crown fire initiation model (Van Wagner 1977) have their limitations, they provide a mechanistic approach to investigate the role of fuel and weather in determining fire behavior. Recent studies by Clark et al. (1996a, b) have presented a coupled atmosphere-fire model which uses a three-dimensional approach to study fire behavior. Such models may provide an even better understanding of fire behavior and the resulting patterns on the landscape such as the effects of large lakes in the forested landscape noted by Bergeron (1991) and Dansereau & Bergeron (1993).

Although fuel accumulation has been shown to play a minor role in fire intensity in the closed canopy boreal forest, this is not necessarily the case in other fire-dominated ecosystems such as ponderosa pine savannas (Cooper 1960; Weaver 1974). In these systems, the absence of frequent surface fires results not only in fuel accumulation but also in a structural change from an open to a closed canopy. Studies in these open canopy systems demonstrating the role of ladder fuels may have led to the general belief of the importance of fuel accumulation in fire intensity.

Discussion

The recurrent theme of the empirical evidence presented here is that the landscape level mosaic of ages created by fire in the boreal forest is primarily determined by large fires resulting from extreme fuel drying weather (Newark 1975; Flannigan & Harrington 1986; Street & Birch 1986; Harrington & Flannigan 1993; Johnson & Wowchuk 1993). Large scale climatic changes which alter the frequency of these extreme weather conditions result in changes in fire frequency over decades to centuries. Thus, the landscape age distribution at any time is a reflection of both the current and past fire cycles. What are some of the implications of these findings for mimicking natural disturbance in forest harvesting and management? Note that, although we limit our discussion here to forest considerations, what we suggest has implications for wildlife as well.

Since the age mosaic of the landscape is created by large fires, these large fires are responsible for producing the diverse age pattern that we see in the boreal forest. Small fires play a minor role in creating this pattern. This conclusion contradicts the widely held belief that large fires homogenize the landscape age distribution. However, the overriding importance of these large fires in creating the diverse landscape mosaic does not necessarily lead to the conclusion that there should be large clearcuts to mimic the effect of wildfire on the landscape age mosaic. Although these wildfires are large in terms of the outside boundaries of the fires, they may not be recognized as large by some of the important ecological processes. For example, silviculturalists have known that tree regeneration is usually determined by distance from the nearest surviving individual tree or clumps of trees which provide either seed or sprout sources. Because of the patterns of mortality within burns, most areas within large fires actually have relatively short distances to the nearest surviving seed sources (Greene & Johnson In press). In contrast to these mortality patterns within burns, often all trees in large clearcuts (except those along stream courses) are removed because of forestry ground rules (e.g. Operating Ground Rules cited in Alberta Forest Conservation Strategy, Anon. 1994). Thus, not only absolute size of burns but patterns of mortality within burns must be taken into consideration.

The landscape age mosaic which consists of small patches of older forest embedded within larger patches of younger forest indicates that old-growth forests did not dominate most of the western boreal landscape prior to arrival of Europeans in North America. This belief in the widespread distribution of old-growth reflects the persistent notion, particularly in the popular literature, that long-term stability is the natural condition. As shown by the fire frequency studies, the intervals between disturbance in the boreal forest have generally been shorter than the generation time of the trees.

There is also an implication in ecosystem management that logging has replaced fire as the principal
disturbance in the boreal forest and that fire has been eliminated or greatly reduced as a major ecological process (e.g. Anon. 1994). The latter may be true in some ecosystems such as the oak savannas and ponderosa pine savannas where fragmentation of these ecosystems (largely due to agriculture, both cattle grazing and crops) prevents the spread of fires. However, in the western Canadian boreal forest, this fragmentation has only occurred along its southern boundaries (Weir & Johnson 1997). The forests are still largely continuous and there is little evidence that suppression of very large fires has been successful. Models and simulations of forests with both harvesting schedules and fire frequency have produced distributions similar in shape to the time-since-fire distribution of unlogged forests, but with steeper slopes (Martell 1980; Van Wagner 1983; Reed 1984; Reed & Errico 1985, 1986). Thus, the additional disturbance by logging would not be expected to change the shape of the landscape survivorship curve but would be expected to increase the slope and decrease the characteristic oldest age of forest (Johnson et al. 1995).

Despite our confidence that fire suppression has been effective, the large areas burned in the past decade and a half (Fig. 4) have caused some concern. The increase in area burned in recent years has been attributed in the popular literature to fuel accumulation in older forests resulting from fire suppression (Kleiner 1996). However, only fine fuels contribute to fire intensity and these fuels do not differ greatly in forests of different ages. Furthermore, fire suppression has rarely been in place in most of the boreal forest for more than 50 yr and this length of time would not have been long enough to result in much older stands. Finally, the time-since-fire distributions have shown synchronous changes in fire cycle in areas with and without fire suppression, suggesting climate change, and not fire suppression, as the driving force behind these changes in fire frequency (Johnson 1992).

We also question the idea of a ‘natural’ fire frequency for the boreal forest. As the fire frequency studies have shown, the present forest landscape mosaic is the result of two or three different fire frequencies over the past 200 - 300 years. Thus we might ask which ‘natural’ fire frequency we would wish to mimic. In light of the correlation between these past changes in fire frequency and climate, we should expect the fire frequency to change as climate continues to change (Flannigan & Van Wagner 1991).

The overriding importance of weather in determining fire intensity (flammability) indicates that the natural processes producing landscape patterns in the boreal forest are operating at a much larger scale than the size of forest management units or jurisdictions (Newark 1975; Johnson & Wowchuk 1993). Also, land use changes (e.g. forest clearance for agriculture) in adjacent areas can often have effects on fire frequency in forested lands by affecting the number of large fires that can spread into these adjacent forested areas (Weir & Johnson 1997).

Finally, even if logging were able to produce the same landscape age distribution as natural disturbance by fire, there would still be significant differences in the impacts of these two disturbances on the forest. We still know relatively little about the specific site effects, such as potential differences in energy and water budgets, of these two disturbances that could have important implications for tree regeneration.

In conclusion, any evaluation of proposals for harvesting practices that attempt to mimic wildfire in their impacts on landscape patterns requires an understanding of the landscape patterns produced by fire. Such an understanding should have an empirical rather than simply intuitive basis. Furthermore, a landscape ecology view of processes should be taken to understand landscape level patterns.

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![Fig. 4. Forested area burned in Canada from 1918 to 1995.](image)
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