19. Modeling of Fire Occurrence in the Boreal Forest Region of Canada

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Introduction

Fire is a significant component of most boreal forest ecosystems. It is important to understand its occurrence and spread to assess the potential impact of global climate change on boreal forest ecosystems. This chapter presents an overview of our understanding of the processes and models that have been developed and used to predict both people-caused and lightning-caused fire occurrences in the boreal forest. We draw heavily on our experience with fire occurrence in the boreal forest region of Canada, but some of our observations may be applicable to other parts of the circumpolar boreal forest as well as other biomes.

We begin by describing the fire occurrence process and the terminology that is used throughout the chapter. We note the importance of weather and provide a very brief description of the Canadian forest fire danger rating system used to predict fire occurrence in Canada. We then describe fire occurrence prediction systems that have been developed and illustrate how they could be used to predict changes in fire occurrence processes that might result from climate change and conclude with a discussion of future research needs.

The factors that influence fire occurrence in the boreal forest include the properties of the forest vegetation, weather, and ignition agents. Fire and forest managers often view forest vegetation as a fuel complex that includes both live and dead vegetation. Common boreal forest fuels include organic soils, leaves, needles, lichen, mosses, twigs, cones, bark, and branches. The chemical composition

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and physical structure of the fuel and its moisture content all play significant roles in determining whether ignition will occur given exposure to a specified temperature for a specified length of time.

Weather plays a significant role in fire occurrence as it determines the moisture content of the forest fuel complex, and lightning ignites many fires in the boreal forest. Fire danger rating systems have been developed to simplify the use of weather data to estimate the moisture content of selected components of a forest fuel complex each day (Stocks et al. 1989).

In Canada, fire danger is modeled by using the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987). Three codes represent the moisture contents of (1) fine fuels (fine fuel moisture code [FFMC]); (2) loosely compacted organic matter (duff moisture code); and (3) the deep layer of compact organic matter (drought code). These moisture codes are derived from daily noon observations of temperature, relative humidity, wind speed, and 24-hour precipitation.

In addition to surface weather variables, the circulation patterns of the upper atmosphere influence fire activity. Sunny skies, warm temperatures, and low relative humidities often accompany the high atmospheric pressure systems. The presence of an upper atmospheric ridge with these high atmospheric pressure systems has been shown to be associated with high fire activity (Newark 1975; Flannigan and Harrington 1988).

Fire Occurrence Process and Terminology

Fire ignition agents are generally separated into two categories—natural and anthropogenic. Natural ignition sources include lightning, which is the most important natural ignition source in the boreal forest. Lightning started 38% of the annual average of 11,000 fires during the 1980s in Canada (Higgins and Ramsey 1992). The remaining fires are mostly human caused and can be accidental or deliberate. A small percentage (3%) of fires is started by unknown causes.

The life cycle of a forest fire can be partitioned into several distinct stages as shown in Figure 19.1. The process begins with the ignition event that occurs when some external heat source such as a discarded flaming match or a lightning strike comes into contact with the forest fuel complex and heats it up to its ignition temperature. The moisture content and other physical properties of the fuel, as well as the ambient weather, will determine the subsequent behavior of the fire. If the fuel moisture content is high but less than the moisture content of extinction (the moisture content above which the fire cannot continue to burn; Rothermel 1972), the fire will continue to smolder and spread very slowly in the duff layer with little or no visible flame. Fires that smolder in the duff layer generally emit very small amounts of energy and smoke and are commonly referred to as smoldering or holdover fires. A holdover fire may be extinguished if the moisture content rises above the moisture content of extinction or it consumes all its fuel.
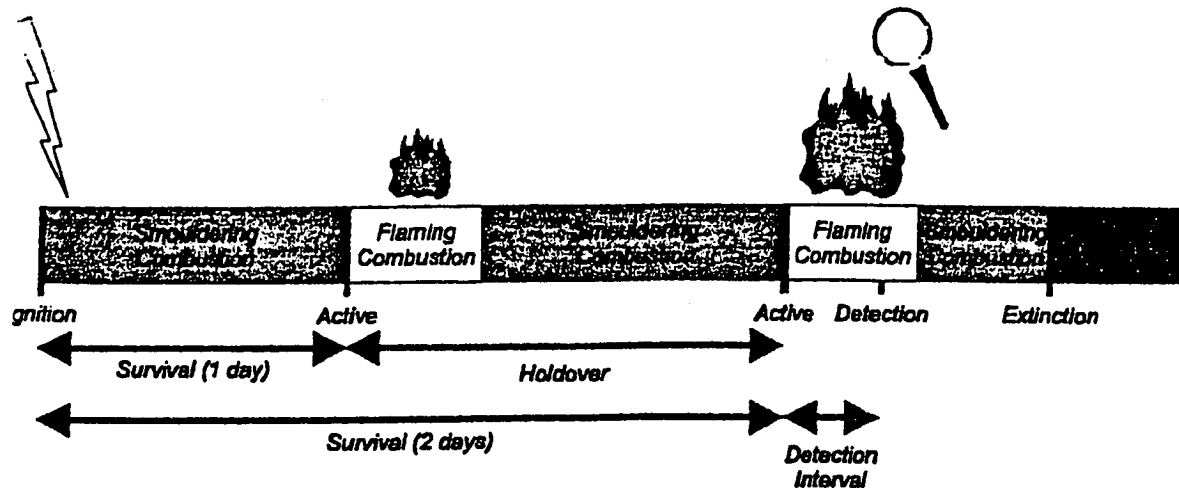
Figure 19.1. Life cycle of a forest fire. The process begins with an ignition from some external heat source, such as a lightning flash or a campfire. The ignition may become active as a flaming combustion or survive smoldering in the forest floor. During periods of peak burning conditions, the smoldering fire may become active by bursting into flaming combustion. The active fire may or may not be detected. In the figure shown, an ignition triggers a smoldering fire. This fire becomes active during the first day but goes undetected, eventually slipping back into a smoldering state. On the second day, the fire becomes active again and this time is detected. It is not actioned but slips back into a smoldering state, ultimately extinguishing itself.

If the holdover fire manages to survive until the weather and fuel moisture conditions reach the point at which sustained spread can occur, the fire will begin to spread through the forest fuel complex as a surface fire or a crown fire and emit significant amounts of smoke and energy. Fires that reach this stage are considered active. Active and smoldering fires that are spotted by people are classed as detections. Fires that are detected and reported to a forest fire management agency are classed as fire arrivals (Cunningham and Martell 1976).[1] The term *fire occurrence* is commonly used to refer to fire ignition and/or arrival, but its meaning is usually clear from the context in which it is used.

Clearly, not all fires will be detected and reported. The probability that an ignition event will lead to a smoldering fire and the probability that a smoldering fire will continue to smolder or begin to spread as an active fire will depend on the condition of the forest fuel complex and the weather. The probability that an ignition event will lead to a detection and arrival will depend on those factors and the presence and behavior of people in the surrounding area. The analysis of fire occurrence processes is complicated by the fact that only reported fires or arrivals are recorded in the records of fire agencies.

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[1]Some forest fire management agencies use the term *fire arrival* to refer to what we describe as an active fire (B. Todd, personal communication).

Modeling Human-Caused Fire Occurrence Processes

People ignite forest fires both intentionally and by accident; therefore, human-caused fire occurrence can be viewed as a random or chance process with parameters determined by demographic, weather, and biophysical factors. Cunningham and Martell (1973) described the theoretical rationale for using the Poisson process to model people-caused fire occurrence. Suppose a large number of persons (n) pass through a forest on a particular day and the probability that any one of them will ignite a fire (p) is very small. The number of fires ignited that day will have a binomial distribution. It can be shown that in the limit as n becomes very large, p becomes very small, and the product of n and p remains constant, the binomial distribution converges to the Poisson distribution with a single parameter $\lambda = np$. The probability that x fires will occur is then given by the following formula for the Poisson distribution (Blake 1979):

$$P(x) = \lambda^x e^{-\lambda} / x! \qquad\qquad (19.1)$$

for $x = 0,1,2, \ldots$.

Cunningham and Martell (1973) presented statistical test results for the Sioux Lookout district of northwestern Ontario that suggest it is reasonable to use the Poisson distribution to model daily people-caused fire occurrence.

Given the Poisson distribution, the challenge is to estimate λ, the expected number of fires per day. It is difficult to incorporate demographic and biophysical variables (see, e.g., Poulin-Costello 1993; Garcia et al. 1995) into fire occurrence estimation procedures. One pragmatic approach for developing estimates of λ is to control for demographic and biophysical parameters by delineating relatively small geographic areas that are reasonably homogeneous with respect to vegetation and land-use patterns. It is then possible to relate daily fire occurrence within that area to fire danger-rating indices observed at a weather station in or near the designated area. Even with such simplifications, human-caused fire occurrence still poses significant parameter estimation challenges due to the small number of fires that occur each day and because the number of fires that occur is not normally distributed, which precludes use of simple linear regression analysis techniques. Several procedures have been developed to circumvent such difficulties.

Cunningham and Martell (1973) used historical observations of the FFMC and daily people-caused fire occurrence to develop an empirical relationship between λ and the FFMC. The FFMC was designed to be representative of the moisture content of fine fuels, which often play a significant role in people-caused fire occurrence processes. They developed a step function that relates the average number of fires per day to the FFMC by partitioning the FFMC into a finite number of subintervals and using historical data to estimate the average number of fires per day for each FFMC category.

The use of step functions to relate daily fire occurrence to fire danger-rating indices is simple to implement but has many limitations. The most obvious is its

failure to capture the smooth nature of changes in the rate at which the average number of fires per day increases as the fire danger increases. Simple linear regression techniques are not suitable because daily fire occurrence is not normally distributed, and very low fire occurrence rates further complicate fire occurrence parameter estimation procedures.

Martell and associates (1987) addressed this problem by using logistic (logarithmic) regression techniques. If one partitions the FFMC scale into a finite number of categories and plots the fraction of days on which fires occur as a function of the FFMC, one often sees a logistic relationship. This observation is consistent with empirical studies of basic fire ignitions processes (see Blackmarr's 1972 work described by Bradshaw et al. 1984). They defined a people-caused fire day as a day during which one or more people-caused fires occur and used a logistic model (Lee 1980; Harrell 1986) to relate the probability of a fire day to the FFMC as follows:

$$P(\text{fire day}) = e^{(a+b\ \text{FFMC})}/[1 + {}^{(a+b\ \text{FFMC})}] \tag{19.2}$$

where a and b are empirically derived coefficients.

Forest fire management agencies typically classify human-caused fires into several categories that reflect the land-use activities resulting in fires. The Ontario Ministry of Natural Resources uses eight people-caused fire categories (recreation, resident, miscellaneous, railway, industrial [forestry], industrial [other], incendiary, and unknown). Fire occurrence also varies seasonally because of changes in plant phenology and land-use patterns. For example, the likelihood that people will cause accidental fires decreases as the season progresses and dead vegetation from the previous year becomes dominated by lush new vegetation. Martell and colleagues (1987) therefore partitioned the fire season into three subseasons (spring, early summer, and summer) and derived logistic models for each fire cause and subseason. Once the probability of a fire day has been predicted, the formula for the Poisson distribution can be used to transform the predicted probability into a prediction concerning λ, the average number of people-caused fires per day.

It is difficult to partition the fire season into a finite number of intervals as it is not clear how many categories should be used or where the boundaries between the subseasons should fall, and significant changes in model parameters can result when one moves across those boundaries. Walker and co-workers (1979) describe how harmonic or periodic regression analysis techniques were used to incorporate seasonal variables in urban fire occurrence prediction models. Martell and associates (1989) adapted these procedures to incorporate seasonal variables in people-caused fire occurrence prediction models. They also aggregated the eight basic fire causes into two broad categories. The approach had the added benefit that one can readily include other variables such as the buildup index, which is thought to influence recreation fire occurrence (e.g., fires that result from campfires). Their periodic logistic fire occurrence prediction system is the basis of the operational people-caused fire occurrence prediction systems used in Ontario, and variants of the technique have been adopted in other parts of Canada.

The basic Poisson model with seasonal and fire danger-rating variables can readily be enhanced. Poulin-Costello (1993) used both logistic and Poisson regression techniques to model human-caused fire occurrence in the Kamloops area of British Columbia. She found that Poisson regression methods produced better predictions than logistic regression methods in relatively dry areas with high fire occurrence rates. Given the widespread availability of statistical software that can be used to carry out Poisson regression analysis, Poisson regression methods should replace logistic regression techniques for fire occurrence prediction models in the future.

Lightning-Caused Fire Occurrences

Lightning is a major cause of fires in the boreal forest. Although lightning fires cause only 38% of the fires, they account for 82% (approximately 2 million ha) of the total area burned nationwide each year. The reason for the disparity in proportions is that most lightning-caused fires occur in remote areas. This results in longer detection times, so that when fire-fighting resources finally arrive, the fires are large. These large fires are difficult to contain, increasing the likelihood of escape. Also, dispatched resources must be transported by air, significantly increasing the costs to contain these fires.

Lightning-caused forest fires are initiated by a cloud-to-ground lightning flash. Not all lightning flashes that strike the forest ignite fires. The likelihood of a lightning flash triggering an ignition is determined by the characteristics of the flash, fuel conditions, and precipitation.

It is generally accepted that long-continuing currents (LCC) present within return strokes of lightning flashes are the cause of ignitions in forest fuel types (Fuquay et al. 1967, 1972, 1979). Unfortunately, little is known about the long-continuing current other than simple observations (Uman 1987) due to the complexities involved in distinguishing strokes with an LCC from those without (Shindo and Uman 1989). Approximately 20% of negative lightning flashes and 85% of positive flashes have a continuing current (Uman 1987).

Latham and Schlieter (1989) used an electric arc generator that simulated lightning discharges (Latham 1987) to study lightning-caused fire ignitions. Simulated discharges were sent through various fuel samples to observe occurrence of ignition. The study showed that the most important predictor of ignition was the duration of the current. The study showed that moisture contents and fuel depth were important factors, too.

The survival or smoldering phase is the time between the ignition of a fuel and the time in which flaming combustion begins. Between these two times, the lightning-caused ignition remains smoldering in the fuel (possibly for several days) until it either dies out or bursts out into active flaming combustion under the right weather conditions.

Hartford (1990) determined a probability of the survival of a smoldering fire within commercial peat moss by using logistic regression with the bulk density,

the moisture ratio, and the inorganic ratio as predictors. The inorganic ratio is the mass of dry inorganics of added soil plus the dry mass of the inherent minerals in the peat over the dry mass of the mineral-free organics.

Under the conditions of the Hartford (1990) study, the probability is that a fire will survive by burning the entire sample (a $9 \times 9 \times 5$-cm block-of peat moss) when ignited on one side. In this study, there were only a few cases of partial burns in which substantial amounts but not the entire sample were burned (W. Frandsen, personal communication). This indicates that extinction occurred within minutes of the withdrawal of the ignition coil. Therefore, Hartford's probability physically represents the probability that a smoldering fire will accelerate to steady state. Once the fire reaches steady state (which typically occurs in the first few minutes), it will continue to burn regardless of time or size, assuming the predictors remain constant.

The final stage of a lightning-caused fire is the active stage at which a smoldering fire bursts into full combustion on the surface. Once a fire reaches this stage, it becomes governed by the three fire behavior components: weather, fuel, and terrain. These are the principal predictors used in the Canadian Forest Fire Behavior Prediction System (Forestry Canada Fire Danger Working Group 1992).

In an operational setting, the active stage alone is not enough to predict a fire occurrence, as the detection ability of forest protection agencies must be considered. Minimum conditions required to sustain combustion are not enough, as a fire may begin flaming combustion, but if it is not spotted by detection efforts, it will simply lapse back into the smoldering stage overnight.

A preliminary survey of lightning-caused fire detections in Saskatchewan's primary protection zone reveals that, on average, lightning-caused fires are detected with head fire intensities of 1,200 kW m^{-1} and at 1.7 m min^{-1} rate of spread. These numbers will vary depending on the detection efforts of protection agencies, but they are indicative of the behavior and intensities required to spot a fire in remote areas.

A probabilistic model can be constructed by calculating the probabilities of each stage of a lightning-caused fire occurrence. Given an individual lightning flash, one can calculate the probability that a lightning-caused fire will occur at a given time t as follows:

$$P(t) = P_{LCC}P_{ign}P_{sur}(t)P_{det} \qquad (19.3)$$

where P_{LCC} is the probability that the flash has a long-continuing current, P_{ign} is the probability of ignition assuming a long-continuing current, $P_{sur}(t)$ is the probability of a smoldering fire surviving until time t, and P_{det} is the probability of detecting a fire in the active stage.

There are a few operational lightning-caused fires occurrence prediction models generally following the probabilistic model described above. Fuquay and assoicates (1979) developed a model of the lightning ignition environment. This model has been generally accepted and has been applied (with variations) by some agencies to predict lightning-caused fire occurrences (Latham 1983; Kourtz and Todd 1991).

Climate Change and Fire Occurrence

Human activities have caused an increase in carbon dioxide, methane, water vapor, and human-made gases such as chlorofluorocarbons and hydrofluorocarbons. These increases in greenhouse gas concentrations are responsible, in part, for the warming of our climate. Global mean surface air temperature has increased by 0.3–0.6°C since the late 19th century (Houghton et al. 1990), with a 1.0–1.5°C rise in temperature observed for the boreal region over the past 30 years (Fig. 1.1).

Fire occurrence should be affected by any climate change that takes place in the boreal forest. Some studies have suggested dramatic increases in fire incidence and area burned in a simulated 2 × CO_2 climate (Overpeck et al. 1990; Flannigan and Van Wagner 1991). However, more recent studies have suggested that there might be a great deal of spatial variability of fire behavior in response to a warmer climate, including areas of decreased fire frequency (Bergeron and Flannigan 1995; Flannigan et al. 1998). The reason for decreasing fire frequency in some regions is the increased precipitation and, more important, the increased precipitation frequency that will be accompanying the increasing temperatures. Other regions may show a dramatic increase in fire frequency if the climate changes according to the general circulation models (GCM) (Stocks et al. 1998).

The amount of ignitions may be directly influenced by changes in the climate. Williams (1992) found a positive correlation between surface temperature and lightning flash rate. Price and Rind (1994) suggest a 30% increase in cloud-to-ground lightning activity for a 2 × CO_2 climate using the Goddard Institute for Space Studies GCM. They estimate that there would be a 44% increase in lightning fires with an area burned increase of 78% for the United States in the 2 × CO_2 environment. Another consideration is the length of the fire season. In Canada, Wotton and Flannigan (1993) predicted that the length of the fire season would increase by 22% (30 days) across Canada using 10 years of daily data from the 2 × CO_2 GCM from the Canadian Climate Centre. Both the increase in lightning activity and the length of the fire season will greatly influence fire occurrence. However, the change in the day-to-day weather associated with a change in climate also needs to be considered. For example, increased lightning activity may be offset due to increased precipitation amount and frequency in some areas. There are indications that some regions will experience an increase in the persistence of blocking ridges in the upper atmosphere (Lupo et al. 1997), which are conducive to increased fire activity.

The weather will also influence the fuel moisture, directly affecting ignition, survival, and arrival of fires. A key factor in determining the fire occurrence in the future will be the precipitation regime. Unfortunately, confidence in the precipitation estimates from the GCMs is low relative to the temperature estimates, although the GCMs are constantly being improved and updated. In a warmer climate, it is likely that overall fire occurrence will increase as a result of increased lightning activity and the increased length of the fire season. Finally, as the climate changes, vegetation cover will also change in response to the changing environment, including disturbance regime (fire, pests, diseases, and windthrow).

A change in the vegetation cover would result in changes in ease of ignition, which, in turn, would influence fire occurrence (Chapter 9).

Research Needs

If global climate change has a significant impact on boreal forest ecosystems, it will affect fire weather, vegetation and forest cover, and land-use patterns. It will also affect fire behavior, which in turn, will influence forest vegetation and land use (Weber and Flannigan 1997). The fire occurrence prediction models that have been developed for fire management planning purposes satisfy such needs reasonably well, but they are not well suited for assessing the potential long-term affects of climate change on boreal forest ecosystems.

There is a need to develop comprehensive models that relate daily fire occurrence to forest vegetation, weather, land-use patterns, and fire management efforts such as prevention. It is clear that the result will be models in which fire danger-rating indices are significant, so it is essential that GCM results are used to generate realistic fire weather scenarios.

One important aspect of fire management is the need to model day-to-day changes in fire weather conditions. Fire management agencies carry out initial attack on new fires as they occur and mount extended attack operations on large fires that result when fires escape initial attack. Initial attack success tends to exhibit serial correlation because fires become more likely to escape after several days of severe burning weather when suppression resources become depleted and the fire danger grows in severity. Martell (1990) has indicated that it is reasonable to model day-to-day changes in the FWI, one of the components of the Canadian FWI system, as a Markov chain. To do this, a GCM-based sequence of days will be required to assess the joint impact of fire management, forest vegetation, and fire weather on fire regimes. Ultimately, higher-resolution regional climate models (Caya et al. 1995) may be required to model fire occurrence under climate change.

If climate change does alter the composition of the boreal forest, it may do so gradually over time. Static models may provide some insight concerning climate change impacts on the boreal forest, but there is an urgent need for dynamic models that can be used to model fire occurrence over long periods of time over which the climate, boreal forest ecosystems, and land-use patterns are changing. There will be a need for fire occurrence prediction models that are compatible with dynamic climate and ecosystem models.

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