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7.3 A MODEL TO PREDICT LIGHTNING-CAUSED FIRE OCCURRENCES

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1. INTRODUCTION

Lightning is a major cause of fire occurrence and forest disturbance in Canada. According to statistics compiled from 1980 to 1989 (Higgins and Ramsey 1992), lightning caused 38% of the approximately 10,000 fires that occur each year in Canada, accounting for 82% (over 2 million ha annually) of the total area burned nationwide.

The ability to predict lightning-caused forest fires would be of great value to forest protection agencies in Canada. Such predictions would assist protection officers in preparing for days with multiple ignitions, routing detection flight paths, and locating holdover fires.

This paper presents a model to predict the probability that a lightning flash will lead to a detectable fire. This model has been implemented as a computer program called the Lightning-Caused Fire Occurrence Prediction (LCFOP) System, which estimates the probability of occurrence and probable locations of lightning-caused forest fires from the current day's lightning activity, forest inventory data and noon weather. Cumulative calculations are used to predict the expected number of ignitions, holdovers, and detectable fires within a region.

2. THEORY

The physical process involved in a lightning-caused fire occurrence has been the subject of study for some years (Anderson *et al.* 2000, Anderson 1993a). This process can be divided into three distinct stages: ignition, survival, and arrival. During the ignition stage, a lightning flash with a long-continuing current triggers an ignition within the forest floor or snag. The ignition then acts as a source for a smoldering fire within the duff layers, capable of surviving for several days. Finally, if fire weather conditions are conducive, the smoldering fire bursts into flaming combustion and the fire is considered to arrive.

2.1 *The Model*

A probabilistic model can be constructed by calculating the probabilities at 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

$$p_{fire}(t) = p_{LCC}\, p_{ign}\, p_{sur}(t)\, p_{arr} \qquad (1)$$

where p_{LCC} is the probability of a long-continuing current, p_{ign} is the probability of ignition assuming a long-continuing current, $p_{sur}(t)$ is the probability of survival for the ignition to smolder until time t, and p_{arr} is the probability of arrival for the smoldering fire.

2.2 *Probability of a Long-continuing Current*

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

Approximately 20 percent of negative lightning flashes and 85 percent of positive flashes have a long-continuing current (Uman 1987). These percentages can be directly translated to $p_{\%LCC}$, the probability of an LCC for one flash of a given polarity (distinct from p_{LCC}, which accounts for direction finder efficiency as described below).

When using a lightning detection network, the possibility that not all flashes are being detected must be considered. Network efficiency can be measured in terms of the percentage of flashes detected by the lightning detection network, which varies spatially based upon the location of the direction finders (Anderson 1993b, Janischewskyj and Chisholm 1992). This efficiency percentage can be interpreted as the probability of detection, p_{DE}, for an individual flash within the network.

The probability of long-continuing current, p_{LCC}, can include p_{DE} by assuming that a recorded flash represents a single detected flash and a number of undetected flashes. The total number of flashes, $N_{flashes}$, can be approximated by

$$N_{flashes} \approx 1 \,/\, p_{DE} \qquad (2)$$

albeit this does produce non-integer results. From this assumption, the probability that none of these flashes have a long continuing current would be

$$q_{LCC} = (q_{\%LCC})^{N_{flashes}} = (1 - p_{\%LCC})^{1/p_{DE}} \qquad (3)$$

where q is the probability of failure, that is, $1 - p$. Thus the probability that at least one of the flashes has a long continuing current is

$$p_{LCC} = 1 - q_{LCC} = 1 - (1 - p_{\%LCC})^{1/p_{DE}}\,. \qquad (4)$$

This approach expands the definition of p_{LCC} to give the probability that at least one flash with a long continuing

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current occurs within the vicinity of a detected flash. It does not quantify how many of the detected and undetected flashes have an LCC.

The approach shown also does not address the problem that there may be undetected flashes in areas currently devoid of any apparent lightning activity. This is a separate problem, which is beyond the current scope of this model.

2.3 *Probability of Ignition*

The ignition phase of lightning-caused fire occurrences can be defined as the process in which a fire, smoldering or flaming, is started in the forest fuels. The likelihood of a lightning flash triggering an ignition is determined by the characteristics of the lightning flash, fuel characteristics and moisture conditions.

Table 1. Ignition probability equations for negative and positive lightning flashes by fuel type, where *mc* is the moisture content (sample weight - dry weight / dry weight), and δ is the fuel depth in cm (Latham and Schlieter 1989).

Fuel	Negative Flash	Positive Flash
Ponderosa pine litter	1.04 exp(-0.054 *mc*)	0.92 exp(-0.087 *mc*)
Punky wood (rotten, chunky)	0.59 exp(-0.094 *mc*)	0.44 exp(-0.11 *mc*)
Punky wood powder (4.8 cm deep)	0.9 exp(-0.056 *mc*)	0.86 exp(-0.06 *mc*)
Punky wood powder (2.4 cm deep)	0.73 - 0.011 *mc*	0.6 - 0.11 *mc*
Lodgepole pine (duff)	$(1+\exp(3.84-0.6\ \delta))^{-1}$	$(1+\exp(5.13-0.68\ \delta))^{-1}$
Douglas-fir (duff)	$(1+\exp(5.48-1.28\ \delta))^{-1}$	$(1+\exp(6.69-1.39\ \delta))^{-1}$
Engelmann spruce (duff)	0.8 - 0.014 *mc*	0.62 exp(-0.05 *mc*)
Peat moss (commercial)	0.84 exp(-0.06 *mc*)	0.71 exp(-0.07 *mc*)

Latham and Schlieter (1989) studied lightning-caused fire ignitions with the use of an electric arc generator to simulate lightning discharges (Latham 1987). In this study, simulated discharges were sent through various fuel samples to observe the occurrences of ignition, with an ignition being defined as a smoldering fire that survives for at least three minutes (Latham pers. comm.). The authors then developed probability of ignition equations for each of the fuel types using logistic regression. These equations are shown in Table 1. The probabilities are based on statistical durations of continuing currents and required inputs for the model include fuel type, polarity of lightning flash, moisture content (*mc*), and fuel depth (δ).

2.4 *Probability of Survival*

Frandsen (1987, 1991a, 1991b, 1991c, 1997) and Hartford (1990) have studied the limits of smoldering combustion. In these studies, smoldering fires were examined in the laboratory using samples of commercial peat moss and, in some cases, forest floor duff. These samples were block-shaped with a basal area of 9X9 cm^2 and a depth of 5 cm. Samples were ignited by placing a heating coil very close to the sample (within millimetres) for three minutes, and then were left to burn.

Using logistic regression, Hartford (1990) determined the probability of the survival of a smoldering fire within commercial peat moss as

$$P_H = 1 / (1 + e^{-19.329 + (17.047) R_M + (1.7170) R_I + (23.059) \rho_I}) \qquad (5)$$

where ρ_I is the inorganic concentration and R_M and R_I are the moisture and the inorganic masses relative to the organic mass, which can be expressed as

$$R_M = mc / (1 - f_I) = mc\ \rho_B / \rho_0 \qquad (6)$$

$$R_I = f_I / (1 - f_I) = \rho_I / \rho_0 \qquad (7)$$

where *mc* is the moisture content (ratio of water mass over total dry mass), ρ_B is the bulk density, ρ_o is the organic density and f_I is the ratio of inorganic mass over total dry mass (Frandsen 1991a) or

$$f_I = \rho_I / (\rho_0 + \rho_I) = \rho_I / \rho_B\ . \qquad (8)$$

The inorganic concentration is obtained from the bulk density and the inorganic ratio as

$$\rho_I = \rho_B R_I / (R_I + 1)\ . \qquad (9)$$

Equation 5 is the probability that a fire will survive by burning the entire sample, under the conditions of Hartford's research. In this study, there were only a few cases of partial burns in which substantial amounts but not the entire sample were burned (Frandsen, pers. comm.). This indicates that extinction occurred within minutes of the withdrawal of the ignition coil. Therefore, Hartford's probability, P_H, physically represents the probability that a smoldering fire will accelerate to steady state. Once the fire reaches steady state, which occurs in the first few minutes, it will continue to burn regardless of time or size, assuming the predictors remain constant.

The probability of survival required for equation 1 must represent the probability that a smoldering fire will survive over a span of time. Hartford's probability does not represent this because, even in a homogeneous fuel, the moisture ratio changes with time, causing P_H to change as well. It is more an instantaneous measure of the probability of survival with no memory of past conditions. Instead, what the model requires is the probability of survival at the most likely time of extinction. Thus the probability of survival, p_{sur}, is the minimum P_H level over time

$$p_{sur}(t) = \min P_H(t) \Big|_0^t . \qquad (10)$$

2.5 *Probability of Arrival*

The arrival phase is the final stage of a lightning-caused fire occurrence at which a smoldering fire translates to flaming combustion on the surface. Once a fire reaches this stage, it becomes governed by the three fire behaviour components: weather, fuel, and terrain - the principal predictors used in the Canadian Forest Fire Behaviour Prediction (FBP) system (Forestry Canada Fire Danger Working Group 1992).

The model currently uses head fire intensity (HFI) and rate of spread (ROS) thresholds of arrival. The probability associated with this decision is a simple step function, intended to provide a clear end to the lightning-caused fire process. If the HFI predicted for the potential arrival is greater than the HFI threshold and the predicted ROS is greater than the ROS threshold, then the probability of arrival is one; otherwise, the probability is zero.

In an operational system, the definition of arrival must incorporate the detection ability of forest protection agencies. 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 may simply lapse back into the smoldering stage overnight. Instead, the thresholds used are the median values of HFI and ROS at time of detection. These can be approximated by surveying historical fire reports (Anderson and Englefield 2001). The median values are used because these represent the conditions at which 50% of fires are detected. Selecting lower values would result in arrivals not likely to be detected, while selecting higher values would result in fires that remain in the system as holdovers past the point of likely detection.

3. METHODOLOGY

To validate the model described by equation 1, each of the probabilities associated with the equation must be provided. Intermediate models used to estimate the probability of ignition and the probability of survival have been described but these models require inputs such as fuel type and moisture content, which need to be determined.

3.1 *LCFOP - the Computer Program*

A computer program has been developed to conduct all the required calculations to solve equation 1. This program, called the Lightning-Caused Fire Occurrence Prediction (LCFOP) System, is closely tied to another program, the Spatial Fire Management System (SFMS): a set of programs that manages daily fire weather and forest inventory and predicts potential fire behaviour within a forest region (Englefield *et al.* 2000). With the SFMS program supplying most of the required data, the LCFOP program can calculate the probabilities needed to solve the model.

The general flow of the LCFOP program is as follows. The program first calculates the overnight survival of smoldering (holdover) fires from the previous day (survival module). Next, the program estimates the probability of ignitions from the current day's lightning activity (ignition module) and the likelihood that these ignitions turn into smoldering fires (survival module). This, combined with overnight survivors, gives the number of smoldering fires for the current day. Present smoldering fires are then tested for arrival (arrival module) to estimate the number of arriving fires for the current day and the number of holdover fires for the next day.

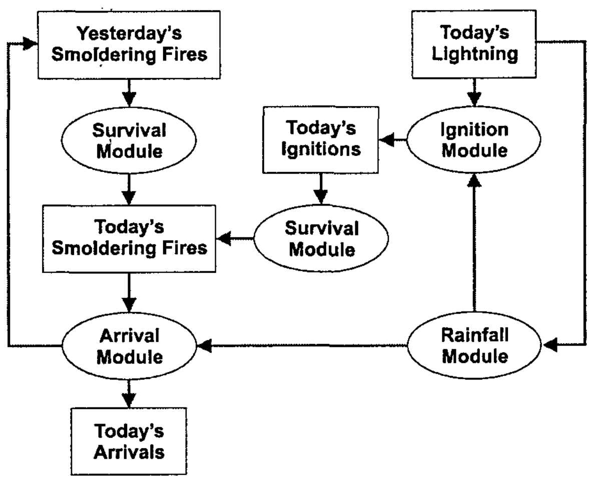

Figure 1. Flow chart for LCFOP.

3.2 *Survival Module*

The first procedure calculates the probability of overnight survival for the previous day's smoldering fires. Equation 10 determines the survival probability, p_{sur}, of the previous day's smoldering fires and survivors are copied to a smoldering fires file for the current day.

To survive, a smoldering fire must survive through the highest moisture content values, which, in the absence of precipitation, occur near dawn for fine fuels. The Canadian Forest Fire Weather Index (FWI) system models the moisture content of the litter and duff layers of the forest floor on a daily basis (Van Wagner 1987). The relationship of the fine fuel moisture code (FFMC) and the duff moisture code (DMC) to the moisture contents of the litter and the duff layers respectively for a generalized standard fuel type are as follows

$$mc = \frac{147.2\ (101 - ffmc)}{59.5 + ffmc} \tag{11}$$

$$mc = e^{(244.72 - dmc)\ /\ 43.43} + 20\ . \tag{12}$$

The FFMC and DMC are interpolated to the location of each smoldering fire (Englefield *et al.* 2000). The FFMC is then diurnally adjusted to 0600 LST conditions by setting it in equilibrium with the environment (referred to as the ECM or equilibrium moisture content). This calculation requires the diurnal variation of temperature, humidity and wind speed, which are predicted in accordance with Beck and Trevitt (1989). Moisture content is then calculated based upon equations 11 and 12 and weighted by the fuel depth, with FFMC used for the top 1.2 cm and DMC for the remainder.

After the moisture content is calculated, Hartford's probability, P_H, is determined for overnight survival using equation 5. Values for the bulk density and inorganic ratio of each FBP fuel type have been defined by Anderson (2000a) and are shown in Table 2.

Table 2. Average duff characteristic values for the FBP fuel types.

FBP fuel type	Duff layer depth (cm)	Bulk density (g/cm²)	Inorganic content
C1	3.4	0.045	0.05
C2	10.0	0.034	0.0
C3	6.5	0.020	0.15
C4	6.2	0.031	0.15
C5	4.6	0.093	0.15
C6	5.0	0.050	0.15
C7	5.0	0.020	0.15
D1	2.4	0.061	0.59
M1/M2	5.0	0.108	0.25
M3/M4	7.5	0.061	0.15
S1	7.4	0.078	0.15
S2	7.4	0.132	0.15
S3	7.4	0.100	0.15

Once the overnight survival probability, P_H, is calculated, it is compared with a minimum probability of survival (set by the user) and with the previous day's probability of survival. If the overnight survival probability is lower than the minimum probability, the record is discarded and the smoldering fire is considered to have died; otherwise, the current day's probability of survival is set to the minimum of either the overnight value or the value from the previous day, in accordance with equation 9, and the record is saved into the current day's smoldering fires file.

3.3 *Ignition Module*

After the overnight survival of smoldering fires is calculated, the probability of ignition is calculated at each of the current day's lightning flash locations and stored in an ignition file. Ignitions go through an initial survival check to see if they can survive as a smoldering fire. These survivors are then appended to the current day's smoldering fires file.

Each lightning flash recorded by the lightning detection system is examined. The forest inventory is then sampled at the location of the flash. If the flash falls outside the area of interest, strikes water or some other non-fuel type, it is immediately rejected.

For negative polarity flashes, the lightning detection network efficiency, p_{DE}, is calculated for the flash location (Anderson 1993b, Janischewskyj and Chisholm 1992) and the probability that the flash has a long-continuing current, p_{LCC}, is calculated using equation 4. The detection efficiency of positive flashes is assumed to be 100% because of their stronger signal strengths.

The moisture content at the ignition location is then calculated as in the survival module, but with the moisture contents diurnally adjusted to the time of the flash and modified by afternoon rainfall.

The probability of ignition, p_{ign}, is calculated using Latham and Schlieter's probability of ignition model. The matching of FBP fuel types to Latham and Schlieter's fuel types is controlled by the user. If the ignition probability is less than a minimum probability of ignition (set by the user), the flash is rejected; otherwise, it is recorded in the current day's ignitions file.

The current day's ignitions are generally sent through the survival module to determine whether the ignition can accelerate to steady-state smoldering conditions. Moisture content values are diurnally adjusted to the ignition time and modified by afternoon rainfall. The decision to send an ignition through the survival module is controlled by the user through the fuel type, as fires can go immediately from ignition to arrival in some fuel types (Latham pers. comm.).

3.4 *Rainfall Model*

A final, important data requirement is afternoon rainfall. Afternoon rainfall is used to modify the fuel moisture conditions in the ignition and initial survival check and in the arrival. Afternoon rainfall is not required for the overnight survival module, which uses the current day's noon weather readings to estimate the previous night's moisture conditions.

Lightning is a result of convective activity and thus is strongly correlated with convective showers. Estimating the rainfall accompanying each thunderstorm is an important requirement; however, this information is not readily available for most of the forested areas of Canada.

Convective rainfall is modelled within LCFOP by assuming a simple relationship. The lightning flash density, which indicates the strength of the convective activity, and the lifted condensation level, which indicates the cloud base height, predict the rainfall following the general formula

$$R = a \times Ltg^{b_1} LCL^{b_2} \quad \textbf{(13)}$$

where R is the rainfall, Ltg is the lightning density in flashes and LCL is the lifted condensation level. The lifted condensation level can be approximated from the surface relative humidity, rh, with

$$LCL = -1.2 \times 35 \times \log_{10}(rh/100) \quad \textbf{(14)}$$

where the LCL is in kilometres above the surface.

The variables a, b_1, and b_2 for equation 13 are defined by the user and can be determined using statistical analysis. Such an analysis was conducted using hourly weather data from three stations in Saskatchewan (Anderson 2000b), yielding

$$R = 0.385 \times Ltg^{0.4893} LCL^{-0.3006} \quad \textbf{(15)}$$

where R is rainfall in millimetres, Ltg is in flashes per hour within a 25 kilometre radius and LCL is in kilometres.

Finally, the model contains a sheltering effect for the ignition and initial survival check, representing rainfall captured by the canopy. The sheltering effect is a user defined value, stating the percentage of the predicted afternoon rainfall removed from the fuel moisture calculations. There is no sheltering effect for the arrival stage.

3.5 *Arrival Module*

The final routine executed is the arrival module. Fire behaviour parameters are predicted for each of the current day's smoldering fires, either at 1700 LST (peak burning conditions) or at the time of ignition, if it occurred after 1700 LST of that day. If the predicted fire behaviour exceeds both the HFI and ROS thresholds, it is moved from the current day's smoldering fires file to the current day's *arrival* file; otherwise, the fire remains in the current day's smoldering-fires file.

Fire behaviour parameters are calculated using the FBP system equations. The required weather values are interpolated and modified diurnally with the estimated rainfall using equation 15. The FBP fuel type is taken from the forest inventory and the fire behaviour is modelled under no-slope conditions.

3.6 *Estimating the Number of Fires*

So far, the emphasis has been placed on calculating the probability that a fire will occur from an individual lightning flash. This is quite useful because individual locations and probabilities can be maintained and presented in map form.

A second output of the program is the total number of expected fires within a region. The probability distribution of lightning-caused fires within a region is binomial, thus the expected number of fires within a region is the sum of the probabilities of each fire within the region

$$E_{fires} = \sum_{i=1}^{n} p_{fire_i} \quad \textbf{(16)}$$

and the variance (the square of the standard deviation) of the expected number of fires is

$$var(E_{fires}) = \sigma^2(E_{fires}) = \sum_{i=1}^{n} p_{fire_i} q_{fire_i} \, . \quad \textbf{(17)}$$

4. RESULTS AND DISCUSSION

A preliminary validation study was run for Saskatchewan. From May 1 to August 31 of 1999, 459 fires were detected in Saskatchewan. The model predicted 424.6 fires during this period with a standard deviation in the prediction of 17.8. These results were based upon using an HFI threshold of 1000 kW/m (no ROS threshold), 100% sheltering of ignitions and resulting smoldering fires from afternoon rainfall, a litter depth of 1.2 cm for all fuel types, and a minimum probability threshold of 0.01 for continued calculations. Results of this study are shown in Figure 2.

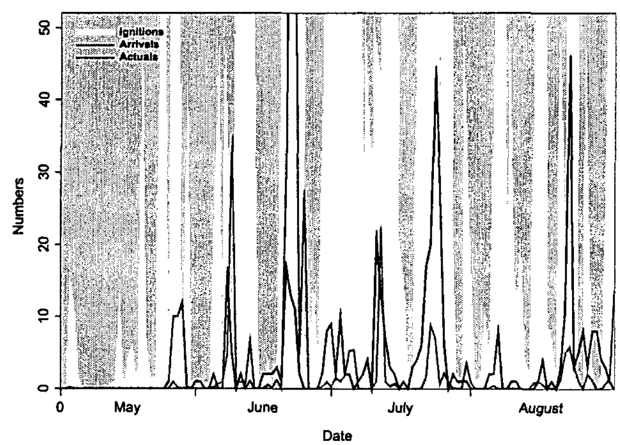

Figure 2. Fire occurrence predictions for Saskatchewan, 1999. Arrivals indicate model predictions, actuals indicate the number of reported fires.

A survey of correct predictions, or days on which the observed numbers of fires fall within the standard deviations of the predicted numbers of fires, show 52 successful predictions out of the 123 days. These successes may be misleading though as there are a large number of successful null predictions – days when the model correctly predicted no fires. While the model should be able to predict no-fire days accurately, there is less skill involved in these predictions and it does little to evaluate the accuracy of the model.

The model appears to be predicting the trends correctly with peaks matching those in the observed data. Sometimes, these predictions are off by a day, such as June 6/7 and July 9/10, suggesting that improvements are required in the survival and arrival modules.

For this preliminary study, the model is either over or under-predicting the daily number of fires, sometimes by as much as a magnitude, making the predicted numbers moot at this stage. There are several possible reasons for these discrepancies. Some of these are controllable within the model, such as fuel type matching, arrival thresholds, sheltering effects, etc., while some are not. Still, the model was able to come within 10 percent of the number of fires for the season and approximate the seasonal trends. This suggests the concepts in the model are correct and that further refinements will lead to a reliable predictive tool.

5. CONCLUSIONS

A model has been developed to predict lightning-caused fire occurrences. The model is physically based, using lightning, weather and fuel conditions to model the probabilities of ignition, survival, and arrival.

A preliminary study shows that for 1999 the model predicted 427.6 compared to 459 actual reported fires for the same period. The model also correctly predicted the daily number of fires on 52 of the 123 days, though many of these were null predictions. The model appears to predict trends in fire occurrence correctly but the predicted numbers of fires is not accurate at this stage. This suggests the concepts in the model are correct and that further refinements will lead to a reliable predictive tool.

6. REFERENCES

Alexander, M.E.; Stocks, B.J.; Lawson, B.D. 1991. Fire behaviour in black spruce-lichen woodland: the Porter Lake project. Info. Rep. NOR-X-310, Forestry Can., Northwest Reg., North. For. Cent., Edmonton, Alberta. 44 pp.

Anderson, K.R. 2001. Quantile characteristics of forest fires in Saskatchewan. *In* 4rd Symp. on Fire and Forest Meteorology, Nov. 12-15, 2001, Reno, NV (in press). Am. Meteorol. Soc., Boston, MS.

Anderson, K.R. 2000a. Incorporating smoldering into fire growth modelling. Pages 31-36 *in* 3rd Symp. on Fire and Forest Meteorology, Jan. 9-14, 2000, Long Beach, CA. Am. Meteorol. Soc., Boston, MS.

Anderson, K.R. 2000b. Predicting convective rainfall amounts from lightning flash density. Pages 166-168 *in* 20th Conf. on Severe Local Storms, September 11-15, 2000, Orlando, FL. Am. Meteorol. Soc., Boston, MS.

Anderson, K.R. 1993a. Lightning-caused fire occurrences: an overview. Pages 27-42 *in* Proc. 6th Western Region Fire Weather Committee Scientific and Technical Seminar, March 23, 1992, Winnipeg, Manitoba. Forestry Canada, Northwest Reg., Nor. For. Cent., Edmonton, Alberta.

Anderson, K.R. 1993b. Calculating lightning detection network efficiencies. Pages 733-738 *in* 17th Conf. on Severe Local Storms/Conf. on Atmospheric Electricity, October 4-8, 1993, St. Louis,Missouri. Am. Meteorol. Soc., Boston, MS.

Anderson, K.R.; Martell, D.L.; Flannigan, M.D.; Wang, D. 2000. Fire occurrence in the boreal forest region of Canada. Pages 357-367 *in* Fire, Climate Change and Carbon Cycling in North American Boreal Forests. *Edited by* Kasischke, E., John Wiley and Sons.

Beck, J.A.; Trevitt, A.C.F. 1989. Forecasting diurnal variations in meteorological parameters for predicting fire behavior. Can. J. For. Res. **19**: 791-797.

Englefield, P.,; Lee, B.S.; Suddaby, R.M. 2000. Spatial Fire Management System. *In* Proc. 20th Annual ESRI User Conference, June 26-30, 2000, San Diego, CA. Env. Sys. Res. Inst., Redlands, CA.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Inf. Rep ST-X-3. Forestry Canada, Science and Sustainable Development Directorate, Ottawa, ON. 63 pp.

Frandsen, W.H., 1997: Ignition probability of organic soil. *Can. J. For. Res.* **27**: 1471-1477.

Frandsen, W.H., 1991a: Burning rate of smoldering peat. *Northwest Sci.*, **65(4)**, 166-172.

Frandsen, W.H., 1991b.: Smoldering spread rate: a preliminary estimate. Pages 168-172 *in* Proc. 11th Conf. Fire and Forest Meteorology, April 16-19, 1991, Missoula, MT. SAF, Bethesda, MD., 168-172

Frandsen, W.H., 1991c: Heat evolved from smoldering peat. *Int. J. Wildland Fire*, **1(3)**, 197-204.

Frandsen, W.H. 1987. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. Can. J. For. Res. **17**: 1540-1544.

Fuquay, D.M.; Baughman, R.G.; Taylor, A.R.; Hawe, R.G. 1967. Characteristics of seven lightning discharges that caused forest fires. J. Geophys. Res. **72(24)**: 6371-6373.

Fuquay, D.M.; Baughman, R.G.; Latham, D.J. 1979. A model for predicting lightning-fire ignition in wildland fuels. USDA For. Serv. Res. Pap. INT-217. Intermt. For. and Range Exp. Stn., Ogden, UT. 21 pp.

Fuquay, D.M.; Taylor, A.R.; Hawe, R.G.; Schmid, C.W. Jr. 1972. Lightning discharges that caused forest fires. J. Geophys. Res. **77(12)**: 2156-2158.

Hartford, R.A. 1990. Smoldering combustion limits in peat as influenced by moisture, mineral content, and organic bulk density. Pages 282-286 *in* Proc. 10th Conf. on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada. AES, Downsview, Ont.

Higgins, D.G.; Ramsey, G.E. 1992. Canadian forest fire statistics: 1988-1990. Inf. Rep. PI-X-107 E/F. Petawawa Natl. For. Inst., Chalk River, ON.

Janischewskyj, W.; Chisholm, W.A. 1992. Lightning ground flash density measurements in Canada, March 1,1984 to December 31, 1991. Canadian Electrical Assoc. report 179 T 382, Montreal, PQ. 106 pp.

Latham, D.J. 1987. Design and construction of an electric arc generator for fuel ignition studies. USDA For. Serv. Res. Pap. INT-366. Intermt. For. and Range Exp. Stn., Ogden, UT. 16 pp.

Latham, D.J.; Schlieter, J.A. 1989. Ignition probabilities of wildland fuels based on simulated lightning discharges. USDA For. Serv. Res. Pap. INT-411. Intermt. For. and Range Exp. Stn., Ogden, UT. 16 pp.

Lawson, B.D. 1973. Fire behavior in lodgepole pine stands. Info. Rep. BC-X-76. Can. For. Serv., Pacific For. Res. Cent., Victoria, BC. 26 pp.

Lawson, B.D; Taylor, S.W. 1986. Preliminary evaluation of prescribed fire impact relationships and predictors for spruce-balsam slash. Fire Management Symposium, Central Interior Fire Protection Committee, Prince George, B.C., April 8-9, 1986. Can. For. Serv. Pacific For. Cent. 20 pp.

Nimchuk, N. 1989. Ground-truthing of LLP lightning location data in Alberta. Pages 33-40 *in* D.C. MacIver, H. Auld, and R. Whitewood, editors. Proc. 10th Conf. Fire For. Meteorol., April 17-21, 1989, Ottawa, Ontario. For. Can., Ottawa, Ontario, and Environ.Can., Ottawa, Ontario.

Quintilio, D. 1972. Fire spread and impact in lodgepole pine slash. M.Sc. Thesis, Univ. Mont., Missoula. 69 pp.

Quintilio, D.; Alexander, M.E.; Ponto, R.L. 1991. Spring fires in a semimature trembling aspen stand in central Alberta. Info. Rep. NOR-X-323, Forestry Can., Northwest Reg., North. For. Cent., Edmonton, Alberta. 30 pp.

Shindo, T.; Uman, M.A. 1989. Continuing current in negative cloud-to-ground lightning. J. Geophys. Res. **94(D4)**: 5189-5198.

Stocks, B.J. 1989. Fire behavior in mature jack pine. Can. J. For. Res. **19**: 783-790.

Stocks, B.J. 1987. Fire behavior in immature jack pine. Can. J. For. Res. **17**: 80-86.

Stocks, B.J. 1971. Development of a jack pine slash burning index in Ontario. Int. Rep. 0-29, Can, For. Serv., Ont. Reg., Sault. Ste. Marie, Ont.12 pp.

Uman, M.A. 1987. The Lightning Discharge. Academic Press, Orlando, FL. 377 pp.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., Ottawa, Ont. For. Tech. Rep. 35.