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2.5 A MODIFIED SUPPRESSION RESPONSE DECISION SUPPORT SYSTEM FOR WOOD BUFFALO NATIONAL PARK

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1. INTRODUCTION

Modified suppression response is becoming an important topic among fire agencies. Deciding whether or not to fight a fire is a choice that fire managers are now faced with. This decision is forced upon the managers because of current fiscal limitations and because of the need to let fire play its natural role in the environment. In making the choice to fight a fire or not, managers need long-range forecasting tools to assess the threat a fire may pose to communities, facilities and other values at risk.

The information required for modified suppression response decisions must be based on a long-range fire growth model that can predict potential fire growth on a scale of weeks or months. This is beyond the scope of current fire growth models (Kourtz *et al.* 1977, Richards 1994) because of their dependency on detailed meteorological data, something that cannot be accurately predicted beyond a few days (Smagorinsky 1967). Thus, the problem of long-range fire growth modelling moves into the realm of climatology and the probability of extreme weather events.

Research has been done on the topic of extreme weather events as they relate to forest fires. Flesch and Wilson (1993) conducted an extreme value analysis of wind gusts in Alberta, which would have a significant bearing on large fire growth. Latham and Rothermel (1993) developed a procedure for calculating the probability of fire-stopping precipitation event. Wiitala and Carlton (1994) combined Latham and Rothermel's model with the probability of a "critical" spread event, giving a model to predict the probability of a fire reaching a geographical point before receiving a fire-stopping rainfall.

This paper is a continuation of the concepts put forth by Latham and Rothermel and by Wiitala and Carlton. The goal of this study is to produce a spatial representation of the probabilities of fire extents over long periods of time to be used as a decision support tool for Wood Buffalo National Park. An emphasis will be placed on Canadianizing any models by incorporating components of the Canadian Forest Fire Danger Rating System (CFFDRS).

2. THEORY

Estimating probable fire extents comprises estimating the probability of fire spread and the probability of a fire extinction over a given time period by

$$p(t) = p_{spread}(t) \times [1 - p_{extintion}(t)] \qquad (1)$$

where $p(t)$ is the probability of a fire reaching a certain point within a given time t, $p_{spread}(t)$ is the probability that the fire will have sufficient spread rates over time to reach the given point and $p_{extinction}(t)$ is the probability of a fire stopping event occurring prior to the fire reaching the given point.

2.1 Spread

The probability that a fire will spread to a location in a given time depends on the variation of the fire's rate of spread over the time period, which is dependant upon fire weather conditions and on the forest fuel types. Assuming an exponential distribution for the rate of spread, the probability of exceeding a rate of spread r_o is

$$p(r > r_o) = e^{-\lambda r_o} \qquad (2)$$

where λ is the reciprocal of the mean of the rates of spread in the distribution.

To make this a spatial problem, a grid of forest fuel types is introduced. The critical rate of spread, r_c, is defined as the minimum rate of spread required to move a fire across a single grid cell in time t. With equation 2, $p(r_c)$, the probability of a fire spreading through one cell in one time period is established.

Assuming that $p(r_c)$ is a binomial probability, the spread through multiple cells over one time period is the product of the probabilities following the path of least resistance. The probability over the same path for n time periods is the same probability raised to the power of $1/n$.

Note that in producing the exponential distribution, several factors must be addressed. The rate of spread exhibits a diurnal trend based upon the changes in temperature, humidity and wind speed over the course

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of a day. By choosing a time period of one day or more, diurnal effects can be eliminated from this part of the calculations. In turn, rates of spread normally measured in metres per minute must be converted to kilometres per day, where diurnal trends must be accounted for.

Another aspect that must be addressed is fire shape. The spatial approach requires a directional component to spread due to predominate wind patterns. For example, the probability of burning across a grid from west to east will be different from the east to west probability. Different rate of spread distributions must calculated per compass direction and they must incorporate a directional component of spread — not just the head fire rate of spread.

2.2 *Extinction*

A fire is naturally extinguished when moisture conditions within the forest floor preclude smoldering combustion. The duff moisture code (DMC) is an index within the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) that estimates moisture contents within the duff layer. When the DMC drops below a certain value, it can be assumed that a smoldering fire will likely expire. This value is called DMC_{ex}, or the DMC of extinction.

The probability that over time the DMC will drop below the level of extinction can be estimated using Markov chains (Olkin *et al.* 1980). Martell (1990) showed that a first order Markov chain can be used to model day to day changes in fire danger. By building such a Markov chain model for the daily changes in DMC, the probability that the DMC may drop from its current level to a level below the DMC of extinction can be estimated.

Markov chain theory is a technique that allows for the measurement of changes in state over time. Given m classes or states, a transitional probability matrix $\boldsymbol{A}$ would be defined as

$$\boldsymbol{A} = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\ p_{21} & p_{22} & \cdots & p_{2m} \\ \vdots & \vdots & & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mm} \end{bmatrix} \tag{3}$$

where p_{ij} is the probability of moving from state i to state j in one step. A logical choice for the step is a single day, since the DMC is measured on a daily basis.

Markov chains allow for modelling of changes in state over several time-steps or days. For a first order Markov chain , the probability matrix after k steps (days) later would be $\boldsymbol{A}^k$.

A transitional matrix for extinction can be built from historical DMC records based upon the number of times the DMC changes from one state to the next. The DMC of extinction can be introduced by modifying the matrix, forcing probabilities associated with values below DMC_{ex} of extinction down to zero, where the probabilities are fixed. In mathematical terms, the probability components of the transitional matrix are changed as follows

$$p_{(DMC \leq DMC_{ex})(DMC=0)} = 1 \tag{4}$$

$$p_{(DMC \leq DMC_{ex})(DMC>0)} = 0 \tag{5}$$

3. METHODOLOGY

The goal of this study is to produce a spatial representation of the probabilities of fire extents over long periods of time to be used as a decision support tool for Wood Buffalo National Park. For this, the geographic information system (GIS) ARC/INFO was used.

Calculating the probability maps consist of work that can be done in preparation, presumably before the fire season and work that must be done at the time of a fire report.

Historical fire weather data were compiled for 13 lookout towers and 2 airports within the park. These data included daily measurements of temperature, humidity, wind speed, direction, and precipitation. In addition, calculations were conducted for the seven FWI indices. The length of records varied from 5 to 30 years.

A forest fuels grid was built from existing park biophysical information data. Information outside the park was supplied from NOAA AVHRR land classification. Fuel types were converted to the Canadian Forest Fire Behavior (FBP) system fuel types (Forestry Canada Fire Danger Group 1992) based upon the expert opinion of park wardens.

3.1 *Probability of Spread*

The probability of spread distributions as described by equation 2 were derived by calculating the rate of spread conditions for each weather record in the historical database for each compass direction (north, northeast, etc.) and for each of the FBP fuel types.

The rate of spread (*ROS*) is an FBP system output that predicts the forward rate at which a fire will spread. Using daily and hourly values from the Canadian Forest Fire Weather Index (FWI) system as inputs, rate of spread can be predicted for a variety of fuel types found in Canada.

The rate of spread was converted to a daily value using diurnal curves of temperature, humidity and wind speed described by Beck and Trevitt (1989). These curves require a variety of meteorological parameters, which were supplied from climate normals for Ft. Smith. The hourly values were used to calculate the hourly fine fuel moisture code (FFMC) and Initial Spread Index (ISI) (Van Wagner 1977).

The directional component of spread was calculated using elliptical fire growth. Assuming the ignition point as the focus, the rate of spread is broken down into direction components using

$$r(\theta) = \frac{(1 - \sqrt{1-1/LB^2}\ )\ r_h}{1 - \sqrt{1-1/LB^2}\ \cos\theta} \qquad \textbf{(6)}$$

where $r(\theta)$ is the rate of spread with respect to deviation from the wind direction θ, r_h is the head fire rate of spread and LB is the length to breadth ratio as determined using the FBP system.

For the exponential distribution, the distribution parameter λ is simply the reciprocal of the mean. Thus, λs of the spread distributions were calculated for each weather station, fuel type, compass direction and month.

Critical spread probability maps — one per month per compass direction — were produced by linearly interpolating the appropriate λ to each cell, based on the fuel type within the cell. Interpolation was conducted with the inverse distance weighted function provided in ARC/INFO grid, although the appropriateness of such an interpolation is yet unconfirmed. Using equation 2, the resulting series of maps show the per cell probability of reaching the critical rate of spread for a given spread direction and month.

A probability of spread map can be created using these series of maps. Given an ignition point and a projection time length, a probability of spread for each cell is calculated by following a path of least resistance as described by equation 3. This path must move from the ignition point to the target cell through the 8 directionally based critical spread probability maps for the current month.

3.2 *Probability of Extinction*

A transitional probability matrix was developed for each weather station from daily DMC values. This matrix comprises one hundred states corresponding to integer DMC values from one to 99. A DMC state of zero was included to indicate the extinct state.

The transitional matrix was used to produce a matrix of probabilities of extinction for each weather station. The matrix is based upon the probability of moving from the current DMC to the extinction state (DMC=0) over time.

A probability of extinction map can be created using values from this matrix. Given a current DMC and a time length for study, probability of extinction values are pulled for each weather station. A map is produced from station probability values using inverse distance weighted interpolation.

3.3 *Fire Extents*

Once the fire spread and the fire extinction probability maps are calculated, the fire extents map is built using equation 1.

4. RESULTS AND DISCUSSION

4.1 *Probability of Spread*

Figure 1 to 3 show a typical rate of spread distribution, in this case for the southwest component of the rate of spread though boreal spruce (C2) for Ft. Smith in July.

The exponential distribution based upon equation 2 is shown to illustrate its appropriateness as a means to describe the observed distribution. While the curve shows the same overall shape, there are departures that may be of concern. In Figure 2, the exponential distribution below a rate of spread of 3 m/min is shown to over-predict the percentile by as much as 20%, while above 3 m/min, the percentile if under-predicted by up to 5%.

In comparison, a least squares fit of the logarithm of the percentile appears to fit the extreme data more accurately, as shown in Figure 3. Yet, this fit over-predicts at rates of spread less than 10 m/min. Given that this represents about 90% of the data, the exponential distribution is deemed more appropriate to use but at the cost of under-predicting extreme values.

While the exponential distribution is superior to the least squares fit, a Weibull distribution may be a more appropriate means to describe the distribution. The disadvantage with using the Weibull distribution would be the necessary computations, i.e., sorting 30 years of data and running regressions for each station, month and compass direction. Still, this will be pursued in the future.

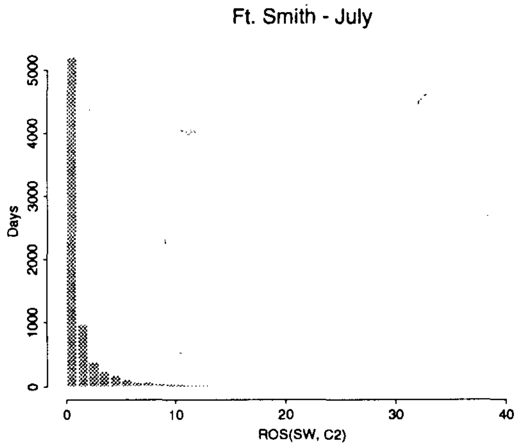

Figure 1. Histogram of the southwest component of noon rates of spread (m/min) in boreal spruce (C2) for Ft. Smith in July.

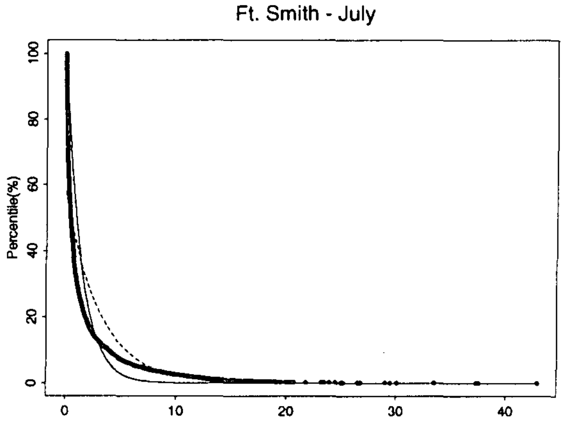

Figure 2. Frequency distribution of southwest component of noon rates of spread (m/min) in boreal spruce (C2) for Ft. Smith in July. The exponential distribution is shown as the solid line. A least squares fit of the logarithm of the percentile is shown as the dashed line.

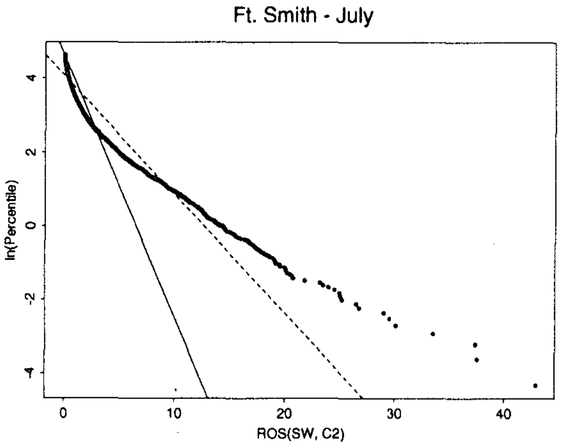

Figure 3. Logarithm of frequency distribution of southwest component of noon rates of spread (m/min) in boreal spruce (C2) for Ft. Smith in July. The exponential distribution is shown as the solid line. A least squares fit of the logarithm of the percentile is shown as the dashed line.

4.2 Probability of Extinction

Figure 4 shows the probability of extinction with time for Ft. Smith in July. The family of solid curves are the probabilities as calculated with the Markov Chains using a DMC of extinction of 20. Individual curves are for a given initial DMC at the time of ignition shown on the right, underneath the corresponding line.

The dashed lines show the observed probability with time based upon a survey of the historical data. Lines from top to bottom correspond to the same initial DMC values as shown by the solid curves. Days since ignition were calculate as the number of days from an initial DMC to the first time when the DMC dropped to below the DMC of extinction. This data was then sorted and assigned a percentile probability.

The figure illustrates the trend of the probability of extinction with time. While the Markov chains show small irregularities in the first few days, the trend is towards smooth curves.

The probability curves produced by the Markov chains appear to agree well with corresponding observed data. The observed data appears ragged due to the few times the DMC matched the initial conditions of 30, 40, and 80 in July (37, 32 and 12 times, respectively).

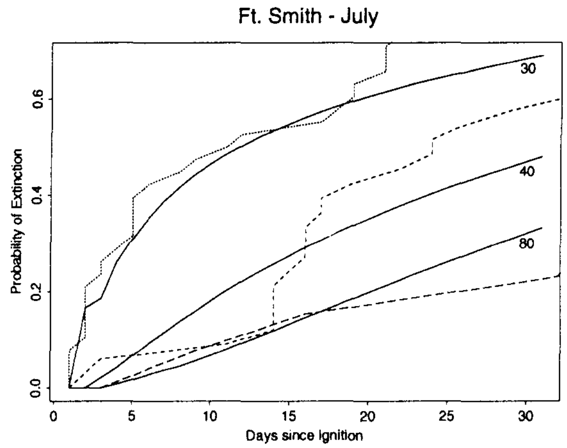

Figure 4. Probability of extinction with time for Ft. Smith in July. Solid lines indicate probabilities curves calculated with Markov chains. Dashed lines are probabilities based upon observations.

4.3 Probable Fire Extents

With methods to calculate the probabilities of spread and extinction defined, maps of probability of spread and extinction can be produced. From these, the probable fire extents map is produced using equation 1.

Figures 5 to 7 show the sequence of maps produced for a 25-day prediction starting July 1 with an initial DMC of 50.

It is worthwhile at this stage to speculate as to the meaning of the probability maps, which is not entirely clear. The fire extents map in Figure 7 shows an area about 100 km in diameter within the 10% contour, yet this does not mean that there is a 10% chance of a fire growing to that size. To the contrary, the map indicates that there is a 10% chance of a fire reaching a given point along the contour line. A fire will most likely burn in a northerly direction or a southerly direction, engulfing portions of the contour, but not equally in all directions. In that sense, one might expect about one-tenth of the 10% contour to burn.

Another aspect hidden in this probability map is that of the fire going extinct at an early stage. There is always the chance that a rainfall might immediately come along, extinguishing the fire at only a few hectares in size.

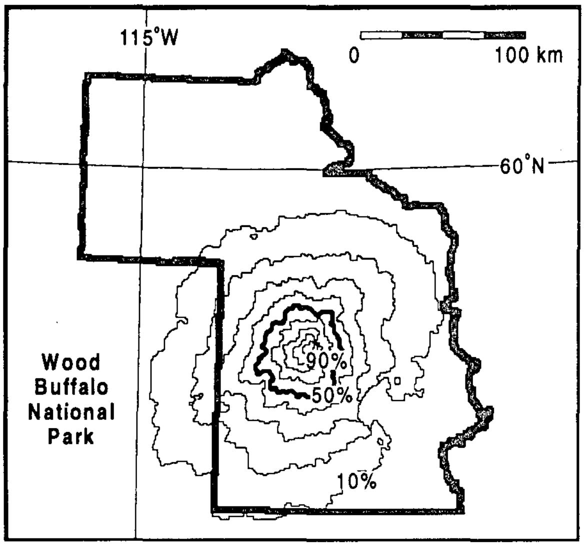

Figure 5. Probable fire spread map for 25-day simulation.

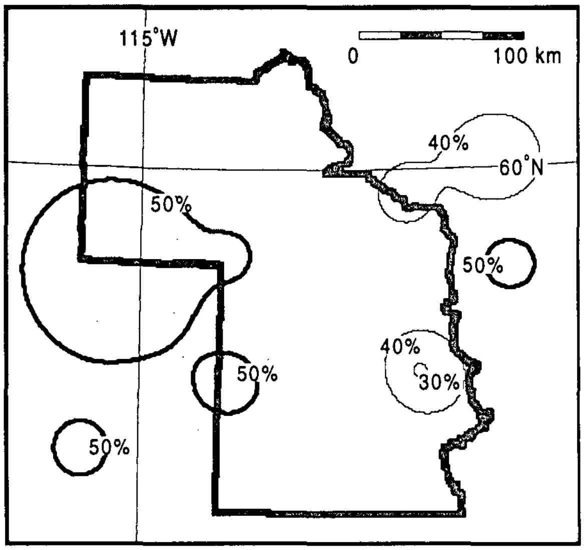

Figure 6. Probability of extinction map for 25-day simulation.

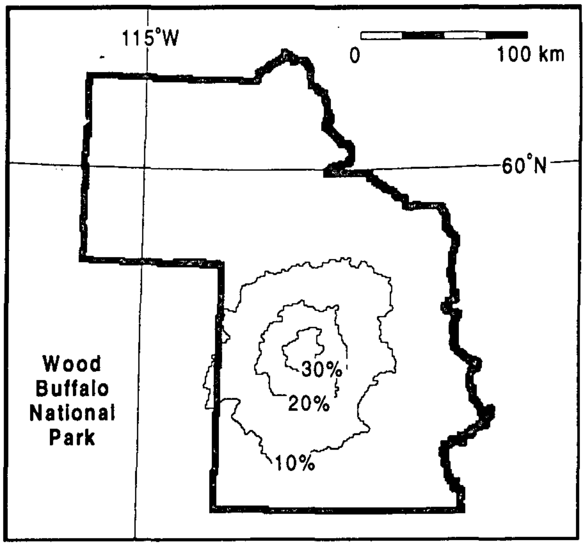

Figure 7. Probable fire extents map for 25-day simulation.

5. CONCLUSIONS

The modified suppression response system developed for Wood Buffalo National Park produces maps of the probability of spread and extinction over time. The combination of these maps gives the probable extents.

The probability of spread is based upon exponential distributions of rate of spread for each month, fuel type and compass direction. It has been shown that the exponential distribution is adequate at describing the observed data, though a Weibull distribution may be superior.

Probability of extinction is determined from the probable evolution of duff moisture code over the fire season. This is predicted using Markov chains and a DMC of extinction. It has been shown that this approach captures very well the observed extinction trends with time.

The model presented in this paper is undergoing continual developments and improvements. While this paper has shown a subjective validation of the sub-components of the system, a validation of the end result will soon be completed.

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