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2.3 INCORPORATING SMOLDERING INTO FIRE GROWTH MODELLING

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1. INTRODUCTION

Smoldering combustion plays an important though somewhat neglected role in the fire environment. It is a determining factor in whether ignitions triggered by lightning will survive from the initial source to reach a point of sustained flaming combustion. This process is not necessarily immediate either as holdover fires can lay dormant, smoldering in the forest floor for days or even weeks (Kourtz and Todd 1992).

Smoldering conditions are also an important aspect to fire suppression and mop-up efforts. Hot spots within a burned area may flare up, serving as an ignition source for future outbreaks.

Frandsen (1987, 1991a, 1991b, 1991c, 1997) and Hartford (1990) have studied smoldering combustion in the lab and through regression analysis have built several probability of survival equations. These models can be used to represent smoldering conditions in the Canadian forest fuel types (Forestry Canada Fire Danger Group 1992) by applying the necessary inputs as described in the literature.

This paper is an application of the work done by Frandsen and Hartford. The necessary information was collected from the literature and tabulated to create equations for the probability of fire survival for the Canadian forest fuel types. Additionally, these survival equations have been incorporated into a simple fire growth model and a spatial fire management system to illustrate possible applications.

2. BACKGROUND

2.1 *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

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

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

$$R_M = mc / (1 - f_I) = mc\ \rho_B / \rho_0 \quad (2)$$

$$R_I = f_I / (1 - f_I) = \rho_I / \rho_0 \quad (3)$$

where mc is the moisture content (ratio of water mass over total dry mass), ρ_B is the bulk density, ρ_0 is the organic density and f_I is the ratio of inorganic mass over total dry mass (Frandsen 1991a) or

$$f_I = \rho_I / (\rho_0 + \rho_I) = \rho_I / \rho_B \quad (4)$$

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

$$\rho_I = \rho_B * R_I / (R_I + 1) \quad (5)$$

Equation 1 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, appears to 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.

Frandsen furthered this work with Lawson, Frandsen, Hawkes and Dalrymple (1997) and Frandsen (1997) to produce probability equations for a number of forest floor types. Taking a general form for the survival equation

$$P_F = 1 / (1 + e^{-[B_0 + B_1\, mc + B_2\, f_I + B_3\, \rho_B]}) \quad (6)$$

where P_F is the probability derived by Frandsen (1997). It is worth noting that the terms used in equation 6 are

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related to but different from those used in equation 1 — moisture content instead of moisture ratio, inorganic fraction instead of inorganic ratio and bulk density instead of inorganic concentration. Equation 1 cannot be rewritten in the more general form of equation 6 without prior knowledge of the bulk density, the organic and inorganic concentration.

2.2 *Moisture Content*

The Canadian Forest Fire Weather Index (FWI) system models the moisture content of the forest floor on a daily basis (Van Wagner 1987). In the FWI system, moisture content is tracked through three indices: the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC), and the Drought Code (DC). These indices respectively correspond to the litter (L), the fermentation (F) and the humus (H) layers. The relationship of these indices to the moisture contents within the respective layers for a generalized standard fuel type are as follows

$$mc = \frac{147.2\ (101\ -\ FFMC)}{59.5\ +\ FFMC} \quad (7)$$

$$mc = e^{(DMC\ -\ 244.72)\ /\ -43.43} + 20 \quad (8)$$

$$mc = 800\ /\ e^{(DC\ /\ 400)} \quad (9)$$

These relationships are referred to as the national standards. In addition to the national standard, Lawson, Dalrymple and Hawkes (1997) produced five fuel specific relationships.

2.3 *Spatial And Temporal Extention*

The probability of survival required for modelling purposes must represent the probability that a smoldering fire will survive over a space and time. The probabilities derived by Hartford and Frandsen (Equations 1 and 6) do not represent this because, even in a homogeneous fuel, the moisture ratio changes with time, causing the probability to change as well. Instead, they are an instantaneous measure of the probability of survival with no memory of past conditions. What is required for modelling purposes is the probability of survival at the most likely time of extinction. Thus the probability of survival, p_{sur}, is the minimum $P_{H,F}$ level over time

$$p_{sur}(t) = \min P_{H,F}(t) \Big|_{0}^{t} \quad (10)$$

Figure 1 illustrates the effect the instantaneous probability has on the model's survival, p_{sur}, over time. In the figure, $P_{H,L}$ varies with time as determined by the variation in the moisture content. As $P_{H,F}$ varies, p_{sur} maintains the lowest value of $P_{H,F}$ with time.

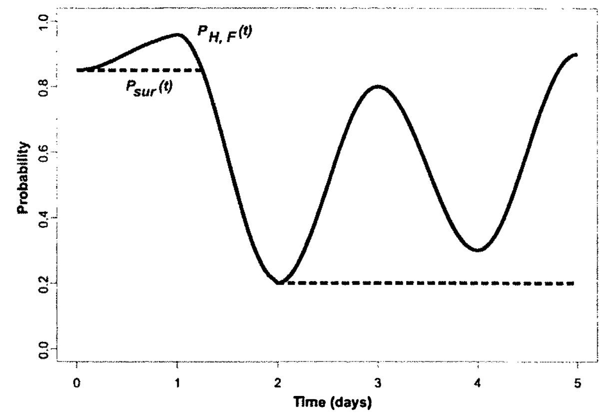

Figure 1. Evolution of the probability of survival over time compared to Hartford and Frandsen's probability of survival value at a given time.

3. METHODOLOGY

3.1 *Survival Equations*

A review of the source literature for the Canadian Forest Fire Behavior Prediction (FBP) system (Forestry Canada Fire Danger Group 1992) was conducted. The intent was to tabulate all required inputs for Hartford's model (equation 1). In turn, probabilities produced using Hartford's model and the tabulated inputs were compared to the probabilities for corresponding fuel types from Frandsen's fuel specific work (1997).

3.2 *Survival Maps*

The survival equations were applied to the Spatial Fire Management System (sFMS) to create maps of the probability of survival. When compared with lightning locations, these maps can be used to locate areas likely to have lightning-caused holdover fires.

The sFMS system is a fire management tool that uses a geographic information system (GIS) to predict potential fire conditions over a region (Lee *et al.* 1997). The system produces spatial maps of fire weather conditions by using noon weather values stored in a database and interpolating these values across the landscape using an inverse distance weighted scheme. Fuel types are created from forest inventory data and stored as a GIS grid (typically 1 km^2 per cell) Interpolated fire weather conditions can be combined with fuels data to produce maps of potential fire behavior based on the FBP system.

Probability of survival maps were produced using Hartford's model (equation 1). Values for the inorganic ratio and inorganic density were collected from literature review and matched with fuel types in the GIS grid. The DMC values were interpolated to each grid cell and moisture contents were calculated using the national DMC equation (equation 8). Moisture ratios for the cells were then calculated using equation 2 and the probability of survival using equation 1.

Table 1. Duff characteristics of the FBP fuel types.

FBP Fuel Type	Load (kg/m^2)	Depth (cm)	Bulk density (g/cm^3)	Inorganic (%)	Source
C1	1.52±0.32	3.4±0.9	0.045±0.015	5	Alexander *et al.* 1991
C2	0.3816 0.6794 1.0297 1.1280 3.2197	0-2 2-4 4-6 6-8 0-8	0.019 0.034 0.051 0.056 0.040	--	Alexander (pers. comm.)
C3 Jack Pine	0.305 0.397 0.637 1.321 1.695±0.309	0-2 2-4 4-6 6-8 LFH: 6.53±0.50	0.015 0.020 0.032 0.066 0.026±0.005	--	Stocks 1989
C3 Lodgep. Pine	0.044±0.010 0.644±0.031 1.545±0.391	L:-- F: 2.10±0.13 FH: 3.22±0.29	-- 0.031±0.002 0.048±0.013	L: 4.36±1.87 F: 16.75±4.09 FH: 23.55±9.41	Lawson 1973
C4	0.440 0.578 0.909 1.181 1.284±0.202	0-2 2-4 4-6 6-8 LFH: 4.58±0.46	0.022 0.029 0.045 0.059 0.028±0.005	--	Stocks 1987a
C5	0.356±0.025 1.753±0.158	Top(L?) Bottom(F,H?)		--	Van Wagner 1963
C6	0.29 2.50	L: 1.4 FH: 5.0	0.021 0.050	--	Van Wagner 1968
C7 Ponder. Pine	--	--	--	L: 4.56±1.56 F: 16.50±2.69 H: 48.08±15.9	Hartford (pers. comm.)
C7 Douglas Fir	--	--	--	L: 4.56±1.56 F: 16.50±2.69 H: 48.08±15.9	Hartford (pers. comm.)
D1	0.30±0.09 2.57±0.59	L : -- FH: 2.37±0.36	-- 0.108±0.025	59±14	Quintilio *et al.* 1991
M1/M2	--	--	--	--	
M3/M4	0.825±0.052 1.214±0.180 1.687±0.286 2.233±0.562 1.975±0.718 7.934	0-2 2-4 4-6 6-8 8+ LFH: 7.5±0.7	0.041±0.003 0.061±0.009 0.084±0.014 0.112±0.028 0.106±0.010	--	Stocks 1987b
O1	--	--	--	--	--
S1	2.132 2.679 2.897	0-2.5 2.5-5.0 5.0-7.5	0.084 0.105 0.114	--	Quintilio 1972
	5.76	7.39	0.078	--	Stocks 1971
S2	9.8	7.39±2.43	0.132±0.044	--	Lawson and Taylor 1986
S3	--	--	--	--	

3.3 *Fire Growth Model*

The probability of survival equation was introduced into a simple fire growth model and survival was calculated for each burned cell. Note that the intent was not to model the spread of smoldering combustion (typically only cm per hour) but to denote areas likely to have smoldering conditions after a fire has passed through.

The fire growth model uses an eight-point propagation routine (Kourtz *et al.* 1977). Spread is calculated in terms of the time of ignition of each cell. For each burned cell, the instantaneous probability of survival at the time of cell ignition was calculated using equation 1. Inputs were based upon the fuel type within each cell and the current DMC. Finally, the instantaneous probability was tracked over time thus showing the probability of survival over time (equation 10).

4. RESULTS AND DISCUSSION

4.1 *Probability of Survival*

Table 1 shows a description of the duff characteristics for the FBP fuel types as collected from the literature review. Average values are shown in Table 2. Note that the grass fuels (O1A and O1B) have not been included as the duff layer is deemed insignificant.

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

FBP fuel type	Duff layer depth (cm)	Bulk density (g/cm^2)	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

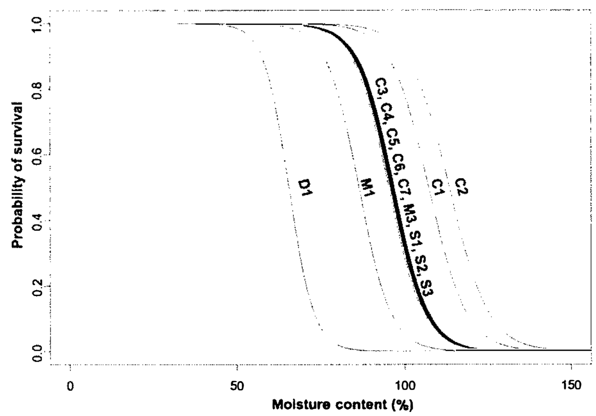

Figure 2. Probability of survival against moisture content for the FBP fuel types .

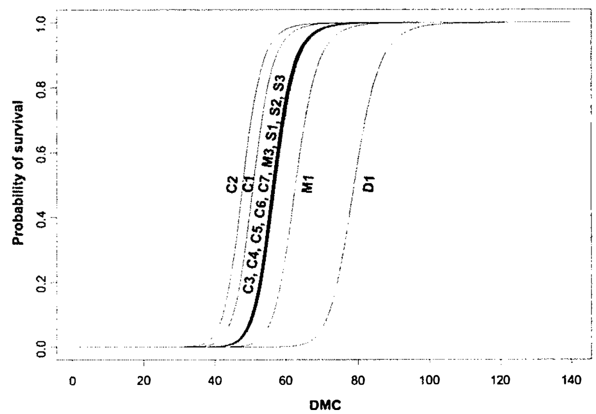

Figure 3. Probability of survival against the duff moisture code (DMC) for the FBP fuel types.

Figures 2 and 3 show the probability of survival curves predicted using equation 1 against moisture content and then against DMC. Apparent from the figure is the commonality of most of the curves, suggesting that the inorganic content has a more significant effect than the bulk density given the values observed in the literature.

Figure 4 shows the probability of survival against moisture content for boreal spruce (C2) using equation 1 and the values in Table 2. Also plotted are the probability of survival curve for reindeer lichen and feather moss from Frandsen (1997), commonly found in the C2 forest floor. The two curves approximately agree on the 50% probability values near the 110% moisture content; yet, the reindeer lichen/upper feather moss has a predictive range broader than that for boreal spruce. This may be a result of noise introduced by foreign substances in field samples, as opposed to the relatively clean, homogenous nature of peat moss.

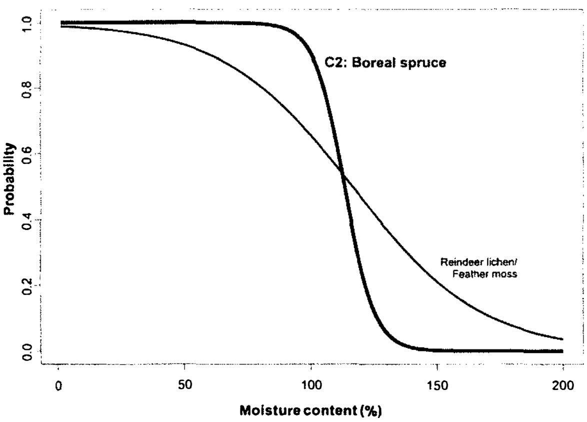

Figure 4. Probability of survival against moisture content for boreal spruce (C2) compared with the probability of survival for reindeer lichen/feather moss.

4.2 *Survival Maps*

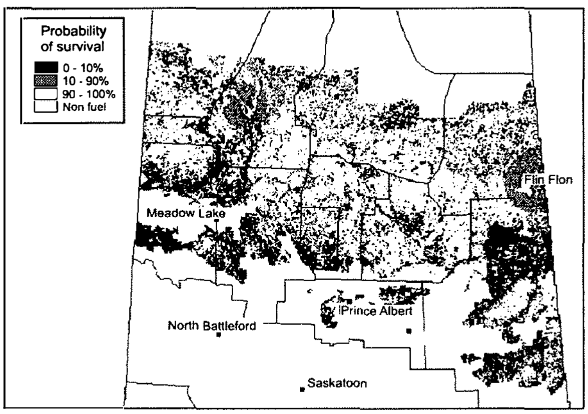

Figure 5. Spatial representation of the probability of survival over central Saskatchewan for May 29, 1995.

Figure 5 shows an instantaneous probability of survival map for the primary protection zone within Saskatchewan, derived from weather values for May 29, 1995 and a 1 km forest fuels grid. Combined with lightning activity, this map would show area likely to have holdover fires. This was a severe fire weather day in Saskatchewan and one can see that holdover fires could be maintained in more than half the forested region.

4.3 *Fire Growth Model*

Figure 6 shows a probability of survival map for a hypothetical fire in Wood Buffalo National Park. This map shows areas within the burned region that are likely to be still smoldering. This would be useful in deciding where to emphasize mop up efforts. Also, it may indicate which areas near the fire line may be a source of flare up, turning a previously contained part of the line into an active fire front.

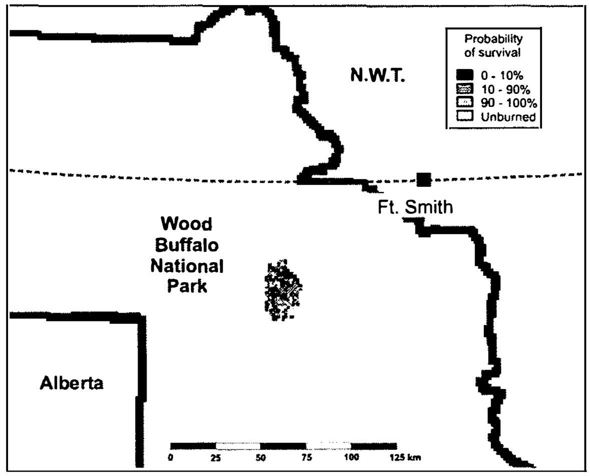

Figure 6. Probability of survival map for a hypothetical fire in Wood Buffalo National Park. This map would show areas within the burned region that are likely to be still smoldering.

5. CONCLUSIONS

Smoldering fire conditions developed by Hartford can be incorporated in various fire models using the inputs collected from the literature.

Frandsen (1997) has provided more fuel specific models, which can be used to improve on predictions, yet at the moment they are limited in scope and do not capture all the fuel types found in the boreal forest. A logical choice would be to use the Frandsen's work, and fall back on the Hartford's more generalized model as required.

Both models were developed in the lab under similar conditions. At this stage, the models are being applied as is without any larger scale validation. This would be the next logical step: seeing that the predictive equations developed for small blocks of fuel can be transposed onto the larger scaled landscape.

A second and equally important future step would be to create reliable duff moisture models. Currently, the models use the national standard DMC to calculate moisture content in the forest floor, but this has serious short-comings. Lawson, Dalrymple, and Hawkes (1997) recognized this and created fuel specific relationships but again, these do not capture all the fuel types found in the boreal forest. Also, shelter plays a significant role in controlling duff moisture content and this must be included in future models.

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