Predicting Ground Fire Ignition Potential in Aspen Communities

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Abstract—*Fire is one of the key disturbances affecting aspen (Populus tremuloides Michx.) forest ecosystems within western Canadian wildlands, including Elk Island National Park. Prescribed fire use is a tool available to modify aspen forests, yet clearly understanding its potential impact is necessary to successfully manage this disturbance.*

Undesirable social consequences of severe, deep burning ground fires include smoke generation and impaired vegetation re-growth. Data on the soil and duff moisture conditions under which ground or subsurface fires may start in aspen are presented, as well as experimental test fire results. Different topographic positions, plant communities and seasons were factored into the research design. The Duff Moisture Code and Drought Code components of the Canadian Forest Fire Weather Index System were calculated and factors including duff moisture content, bulk density and inorganic content measured at the time of ignition. Probability of sustained smouldering ignition models were developed for the aspen forest fuel type, with values of 27 for DMC and 300 for DC at the 50% probability of ignition level. This information will improve the capability to effectively manage aspen using fire in central Alberta.

Introduction

The Duff Moisture Code (DMC) and Drought Code (DC) within the Canadian Forest Fire Weather Index (FWI) System (Canadian Forest Service 1984; Van Wagner 1987) are values of great assistance to fire managers in assessing forest fuel dryness and associated fire risk. Both DMC and DC represent soil duff (i.e. LFH) moisture dryness (Van Wagner 1987), and therefore, its potential to influence fire behaviour. Changes in DMC track moisture in the shallow duff or fibric soil horizon (F-layer), while the DC tracks the humus (H) or deep duff layers as well as heavy downed woody materials. Both indices are determined at noon (standard time) each day during April to October from the standardized weather readings of dry-bulb temperature, 10 m open wind speed, relative humidity and 24 h accumulated precipitation (Turner and Lawson 1978).

Currently there are empirical models correlating the probability of smouldering combustion or ignition and DMC-DC values for select boreal forest types using commercial peat moss as a fuel source (Frandsen 1987, 1991, 1997; Hartford 1989; Lawson and others 1997), but none for trembling aspen. EINP is dominated by trembling aspen (*Populus tremuloides* Michx.) forest. Although these communities may not burn as readily as other boreal forests in the Boreal region (Peterson and Peterson 1992), ground fire may persist in this vegetation under dry conditions for extended periods (Lawson and Dalrymple 1996).

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In this study, the probability of sustained combustion or ignition was examined for soil duff layers in aspen forests of Elk Island National Park, with ignition tests conducted *in-situ*, as per the Lawson and others (1997) field trials. We also determined whether the indices of modeled DMC-DC predict ignition in aspen forest equal to that of duff moisture, with or without soil bulk density and inorganic content considerations.

Materials and Methods

Study Area

EINP is situated 35 km east of Edmonton in central Alberta (approximate Lat. 53° N; Long. 112° E), at the north end of the Beaver Hills,a post-glacial dead-ice moraine elevated 10 to 30 m above the surrounding plains, sufficient to place the area within the Lower Boreal Mixedwood ecoregion (Strong and Leggat 1991). The dominant vegetation of uplands in the Park is trembling aspen, although open grasslands, shrublands, and white spruce [*Picea glauca* (Moench) Voss] forests are interspersed throughout the area (Polster and Watson 1979). Six different aspen plant community types have been identified within the Park (Best and Bork 2004).

The climate of the area is cool-continental, with long, cold winters and short, warm summers (Bowser and others 1962). Annual precipitation over the last 44 yrs at the Edmonton International Airport indicates an average yearly rainfall of 460 mm (Parks Canada 2004). Precipitation in the Park from April to October, inclusive, accounts for 81% of yearly totals (Parks Canada 2004), and has ranged from 220 to 470 mm over the last 10 yrs (Parks Canada 2004). Mean growing season temperatures vary between 5°C in April to 17°C in summer (Rogeau 2004), while the frost-free period is about 100 days (Crown 1977).

Both DMC and DC are re-calibrated annually beginning at 'start-up', either 3 days after snow loss in spring or 3 days after a recorded noon temperature of 12°C (Alexander 1983; Canadian Forestry Service 1984), and are continually updated throughout the fire season until October 31st (Turner and Lawson 1978).

Experimental Approach

The approach used in this study was to develop and test empirical relationships between DMC-DC and ignition trials from various sites throughout the Park. A main calibration site was utilized, involving intensive, repeated sampling and testing to establish a detailed profile of burning success under various DMC-DC levels. Sampling was performed both within *in-situ* soils as found within each plot, as well as within 'rainfall exclusion' treatment areas, designed to exclude precipitation and simulate drought (Van Wagner 1970). Exclusion areas were 3 x 3 m, and tarped 1 m above ground to eliminate soil moisture recharge and to ensure low moisture levels (and high FWI values) were represented in at least a portion of the plots where test fires were conducted. Following initial calibration of codes to the primary ignition plots, relationships between ignition and DMC-DC were subsequently tested on independent replicated plots within each of three main aspen plant community types found throughout EINP (Best and Bork 2004).

Field Sampling

All plots were 20 x 20 m in size and permanently marked. The calibration area was situated within a plant community type encompassing traits similar to the two most prevalent types previously documented within EINP, accounting for approximately 70% of all aspen communities previously investigated within the Park. On average, there were two ignition tests within each plot on each day of sampling. Twelve validation plots were randomly selected from a series of 96 vegetation permanent sample plots (PSP) situated on forested uplands throughout EINP.

Daily fire weather observations were obtained from the Environment Canada (Campbell Scientific) automated weather station, 800 m from the calibration site. Precipitation was also measured locally within and adjacent to the calibration site and at each validation site using a manual rain gauge. Unique fire weather indices (DMC-DC) were calculated for each site using localized precipitation and all other observations were from the weather station.

Ignition Testing and Analysis

Most tests took place during the months of May to August 2004, on a schedule frequent enough to coincide with small increases in DMC-DC and to ensure a series of ignitions ranging from 0 to 100% success at each site. Ignition trials were conducted similar to the method used by Lawson and others (1997). Core samples were taken in each plot as per Nalder and Wein (1998), using a cordless drill and hollow, cylindrical tube auger, 5 cm in diameter. Extracted core samples were separated into 2-cm increments and later oven-dried to determine the moisture content and bulk density of each layer. Core holes from moisture sampling were then filled with smouldering peat moss, obtained from commercial supplies. Peat was heated until approximately $^2/_3$ black in colour and actively smouldering, producing greyish-black smoke. The 5-cm diameter and 12- to 15-cm deep hole generally required about 500 ml of peat moss. Heated moss was carefully placed into the hole, with slight overfilling to compensate for the eventual collapse of peat moss during combustion. Test holes typically smoked for 2 to 5min until a grey ash cover formed.

After 2 h had passed, the peat was carefully removed, making sure not to scrape the sides of the drill hole at the combustion interface. Bare fingers were used to promptly test the perimeter of the hole throughout the 2- to 4-cm and 4- to 6-cm layers for evidence of persistent ignition. The proportion of the cylindrical core found smouldering corresponded to the reported percentage of success or probability of ignition, to the nearest 10%.

All extracted soil core samples were measured for duff moisture and bulk density using the procedure of Lawson and Dalrymple (1996). A representative number of soil core samples were retained for inorganic content determination, following the methods of Kalra and Maynard (1991). A total of 117 trials were carried out, with 64 on the calibration site and 53 on the validation sites. In most areas the 'burning window', ranging from 0% to 100% success, was duplicated at least twice.

Data Analysis

The variables utilized in all analyses included DMC-DC, moisture content (% oven-dry weight basis), bulk density (kg m^{-3}), and soil inorganic content (ash, reported as %). To arrive at one model comparing the probability of ignition success versus the corresponding observed DMC-DC, a non-linear procedure, PROC NLIN (SAS 2001), was used and fitted to a logistic model.

The first analysis involved comparing the probability of ignition versus the DMC or DC only on the calibration plots. Coefficients derived from initialization were run on SAS to check for convergence and derive the B_0 and B_1 values of the estimates. The B_0 and B_1 parameters from SAS were then inserted into a simple non-linear regression model. The standard formula used was:

$$P=\exp(B_0+ B_1*Code)/(1+\exp(B_0+ B_1*Code)), \quad (1)$$

where 'Code' represents DMC-DC, B_0 the intercept and B_1 designates the slope of the regression coefficients. To confirm the relative accuracy of the calibration equations generated, a linear regression analysis was used to determine the goodness of fit (R^2) and other statistical parameters of the models in relation to the actual probabilities observed.

The second analysis included development of a multivariate non-linear regression model, which included DMC-DC, bulk density (ρ_B) and soil inorganic content (Ash), using the following formula, after Lawson and others (1997):

$$P=\exp(B_0+ B_1*Code+B_2*Ash+B_3*\rho_B)/$$
$$(1 +\exp(B_0+ B_1*Code+B_2*Ash+B_3*\rho_B)) \quad (2)$$

where 'Code' represents DMC-DC, B_0 the intercept and B_1, B_2 and B_3 designates the slopes as regression coefficients. For the multivariate non-linear regression analysis, the simple equation coefficients B_0 and B_1 were utilized as a starting point, and when combined with the average inorganic content and actual bulk density measurements, as per Lawson and others (1997), used to initialize the approximate B_2 and B_3 coefficients. Only the DMC or DC value was changed at any one time to form the new multivariate models that were checked against the results of the field trial ignition probabilities. Next, these approximate coefficients were inserted into SAS (SAS 2001) along with the actual data set of varying bulk density values and different average inorganic values from 2003 and 2004. Finally, the derived coefficients were run once more with the average bulk density and inorganic values in the multivariate non-linear regression model run with SAS. Multivariate equations were also assessed for goodness of fit (R^2) and other statistical parameters through linear regression with the actual ignition probabilities measured.

The 53 validation site trials were subsequently tested against the calibration models by comparing actual validation ignition success rates (probability values) against the predicted results expected from the simple non-linear calibration models. Testing involved the evaluation of goodness-of-fit (R^2) and other statistical parameters obtained through the use of linear regression with PROC REG (SAS 2001).

Both the calculated moisture content and corresponding DMC-DC values were compared against observed ignition trial results through linear regression with PROC REG (SAS 2001) to determine any differences between predictive capabilities. Finally, results were compared to modelled ignition probabilities from Lawson and others (1997), utilizing the results modelled at the 50% probability level, as suggested by Cruz and others (2003).

Results

Calibration Results

Results of the ignition analysis generated from the calibration site data are provided in table 1, and indicate that both the simple and multivariate models for both the DMC and DC layers were highly significant ($P<0.0001$). However, overall R^2 values were greater, and root mean square error (RMSE) and coefficient of variation (CV) values less for models generated using the DMC layer compared to results for the DC (table 2). While the simple and multivariate models resulted in similar R^2, RMSE and CV within the DMC data, the simple model resulted in a greater R^2 and lower CV than the multivariate model within the DC data (table 1).

Final coefficients for both the simple and multivariate models in the DMC and DC are shown in table 2. Simple and multivariate non-linear models were additionally compared graphically within each of the DMC and DC (fig. 1). Results indicate that the simple model predicted a slightly greater probability of ignition than the multivariate model at a given DMC-DC code, although this difference was more apparent within the DC data (fig. 1). This finding indicates the addition of soil bulk density and inorganic content to the model tended to reduce the anticipated probability of ignition. For example, the simple model indicated a 50% probability of ignition at DMC and DC values of 27 and 300, respectively (fig. 1). In contrast, DMC and DC codes resulting in the same ignition, but using the multivariate model, were 29 and 336. Given that the results from either model were similar, and because

Table 1—Linear analysis of calibration site DMC and DC values, and observed probability of ignitions using simple or multiple regression modelled equations, showing goodness of fit (R^2), root mean square error (RMSE), coefficient of variation (CV) and probability (Pr>F).

		Linear Analysis			
Code	Model Type	R^2	RMSE	CV	Pr>F
DMC	Simple Equation	0.74	0.14	16.69	<.0001
	Multiple Equation	0.74	0.15	18.72	<.0001
DC	Simple Equation	0.54	0.23	50.42	<.0001
	Multiple Equation	0.43	0.24	80.93	<.0001

Table 2—Coefficient parameters and standard errors for simple and multiple non-linear models comparing DMC and DC values to the probability of ignition in the aspen fuel type at EINP.

Code	Model Type	B0	SE[a]	B1	SE	B2	SE	B3	SE	F	Pr>F
DMC	Simple[b]	–3.11	0.63	0.12	0.02	–	–	–	–	1008.31	<.0001
	Multiple[c]	2.92	1.38	0.12	0.02	–0.16	0.05	–0.002	0.001	485.68	<.0001
DC	Simple	–8.96	2.22	0.03	0.01	–	–	–	–	147.14	<.0001
	Multiple	7.98	3.03	0.04	0.01	–0.36	0.08	0.0002	0.001	127.55	<.0001

[a] Standard error.
[b] Simple non-linear equation is P=exp(B0+ B1*Code)/(1+exp(B0+ B1*Code)).
[c] Multivariate equation is P=exp(B0+ B1*Code+B2*Ash+B3*ρB)/(1 +exp(B0+ B1*Code+ B2*Ash+ B3*ρB)).

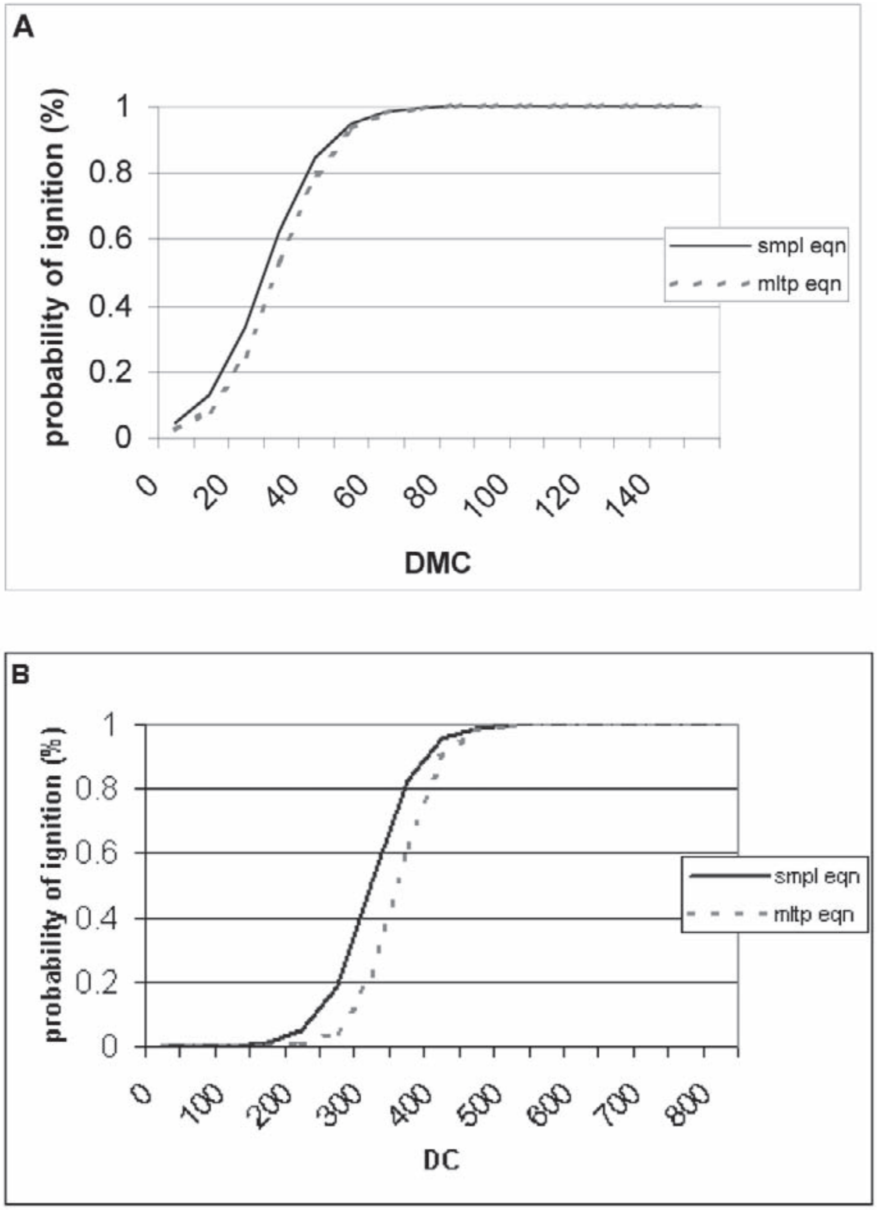

Figure 1—Results of the non-linear analysis fitted to a logistic model showing the probability of sustained ignition against the DMC (A) and DC (B) for simple (smpl) and multivariate (mltp) equations.

inorganic soil data were limited, the simple models were chosen for subsequent application to the validation data.

Validation of Ignition Prediction Models

Ignition probability values observed at the validation trials were compared directly to the values predicted using the simple model developed from the calibration site for both DMC and DC layers. For the DMC, a strong relationship ($P \leq 0.001$) was evident between observed and predicted ignition, but only at the Beaver and Tawayik sites (table 3), with no relationship ($P = 0.52$) at the Goose site. Goodness-of-fit comparisons for the former two were

Table 3—Comparison of the validation observed field burning data to the calibration site modelled results using simple linear regression, showing goodness of fit (R^2), root mean square error (RMSE), coefficient of variation (CV) and probability (Pr>F).

		Linear Analysis			
Code	**Validation Site**	**R^2**	**RMSE**	**CV**	**Pr>F**
DMC	Beaver	0.49	0.20	31.12	0.0006
	Goose	0.04	0.26	34.67	0.5216
	Tawayik	0.46	0.23	33.85	0.0013
DC	Beaver	0.50	0.11	78.05	0.0004
	Goose	0.54	0.22	49.84	0.0029
	Tawayik	0.33	0.23	80.79	0.0102

relatively strong (R^2 = 0.46 to 0.49), with a positive relationship between predicted and observed ignitions (table 3). Results of the DC analysis were similar to DMC, except that a significant relationship ($P \leq 0.01$) was evident between actual and observed ignition at all three validation sites (table 3). Goodness-of-fit values for the three sites were similar (R^2 = 0.33 to 0.54) to those observed previously with the DMC.

Comparison of Moisture Content and FWI System Fuel Moisture Codes on Ignition Success

Regressions of ignition success with either moisture content or DMC-DC were compared for each soil layer (table 4). Results from the calibration site and the total pooled data from all validation sites were analysed for both F and H-layers. In all comparisons except the calibration F-layer, FWI values of DMC-DC were superior predictors of ignition than soil duff moisture. FWI values had a higher goodness-of-fit (R^2 = 0.20 to 0.53) and lower RMSE (23 to 35) and CV (27 to 89%) than moisture content comparisons. All FWI comparisons were significant ($P < 0.001$).

Table 4—Comparison of observed ignition success versus either moisture content (MC) or the FWI codes of DMC/DC, showing goodness-of-fit (R^2), root mean square error (RMSE), coefficient of variation (CV) and probability (Pr>F) for the calibration site (Allcal) and combined validation data (Allval).

		Linear Analysis			
Soil Layer	**Parameter**	**R^2**	**RMSE**	**CV**	**Pr>F**
F-layer	Allcal MC	0.62	18.94	22.42	<.0001
	Allcal DMC	0.44	23.02	27.26	<.0001
	Allval MC	0.02	33.68	40.00	0.2899
	Allval DMC	0.20	30.37	36.06	0.0007
H-layer	Allcal MC	0.25	40.32	74.47	<.0001
	Allcal DC	0.53	31.98	59.07	<.0001
	Allval MC	0.07	44.14	110.35	0.0570
	Allval DC	0.40	35.45	88.63	<.0001

Comparison of Results to Other Models

Comparison of the modeled values derived here to Lawson and others (1997) indicate the ignition results from EINP were associated with lower DMC-DC values relative to similar ignition probabilities in boreal forest duff types elsewhere. At the 50% probability of ignition, Lawson and others (1997) calculated DMC values between 39 and 58 in upper feather moss and upper sphagnum moss vegetation. Using the lower feather moss fuel type, the Lawson and others (1997) DC value at the 50% probability was 482. In Anderson (2000), the 50% probability of ignition for the DMC layer in the D-1 (leafless aspen) fuel type was calculated near 79, although the logistic regression model utilized in that study was from Hartford (1990).

Discussion

Using the simple ignition models developed in this study, code values of 27 and 300 for DMC and DC, respectively, were determined to approximate the 50% probability of ignition. Incorporating inorganic content and bulk density into multivariate predictive models led to minimal changes in threshold code values (DMC 29 and DC 336 for 50% probability). The addition of physical fuel properties only marginally improved the predictability of ignition models. Both Frandsen (1987) and Lawson and others (1997) developed multivariate equation models for certain duff types; however, neither definitively compared the accuracy of simple and multivariate models. Ignition tests in these studies were also recorded as binary events (yes or no), whereas in the current study a range of probabilities were recorded to a finer resolution (0.0 to 1.0).

Model goodness-of-fit values based on comparison of the validation to calibration data indicated ground fire occurrence could be predicted to some degree from calibrated ignition models. Variation in model accuracy may be explained by the shallow nature of the surface duff profile and substantial inorganic content and bulk density values found in duff layers of the Park.

Validation ignition models for the DC layers, while significant, were found to have a lower R^2 and higher CV than those for the DMC. The shallow depth of the DC layer, coupled with a high inorganic content may explain these observations.

Ignition was under-estimated by calibration models on average at actual ignition levels over 60% for DMC and 20% for DC. Ignition success in the field often increased from less than 20% to over 50% and above, over a very short time interval (days). Ignition also appeared to change rapidly with moisture depletion and changing FWI codes. As a result, effective modelling of ignition remains difficult under rapidly changing environmental conditions, in turn affecting the accuracy of ignition models.

The smouldering threshold (i.e. 50% probability of ignition) for the DMC and DC in ignition trials of Lawson and others (1997) were much greater than that observed in the current study. Lawson and others (1997) also found that a narrow range of moisture separated successful from unsuccessful ignitions, particularly in white spruce duff, somewhat similar to observations within the current study where ignition increased from 20% to more than 50% over a few days.

Conclusions

This research established and tested non-linear models relating DMC and DC to the probability of duff ignition, or ground fire. Overall, simple rather than complex multivariate models were more effective in relating DMC and DC to ignition. During the validation procedure, models developed for the independent calibration site were relatively effective at detecting a change in ignition, although the accuracy of those models remained quite low.

Results of this study indicate that the aspen forest and D-1 fuel type of EINP is quite unique in its properties. Thus, the results of this study are not directly comparable to either that of Frandsen (1987) or Lawson and others (1997) in conifer vegetation types.

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