# Role of vegetation and weather on fire behavior in the Canadian mixedwood boreal forest using two fire behavior prediction systems

**Christelle Hély, Mike Flannigan, Yves Bergeron, and Douglas McRae**

**Abstract**: Spring and summer simulations were carried out using the Canadian Fire Behavior Prediction (FBP) and U.S. BEHAVE systems to study the role of vegetation and weather on fire behavior in the mixedwood boreal forest. Stands at Lake Duparquet (Quebec, Canada) were characterized as being deciduous, mixed-deciduous, mixed-coniferous, or coniferous, according to their conifer basal area percentage. Sampled fuel loads (litter, duff, woody debris, herbs, and shrubs) and local weather conditions (three different fire-risk classes) were used as inputs in the simulation. The predicted fire behavior variables were rate of spread (ROS), head fire intensity (HFI), and area burned. Results from ANOVA testing showed that both weather and vegetation are not always significant, and the two prediction systems qualitatively attribute the explained variance to these factors differently. The FBP System selects the weather factor as the most important factor for all fire behavior variables, whereas BEHAVE selects the vegetation factor. However, three research burns located in Ontario revealed that BEHAVE was not well adapted to the mixedwood boreal region, whereas FBP predictions were quantitatively close to observed prescribed values. Extreme fire weather is confirmed as producing large and intense fires, but differences in fire behavior among stand types exist across the full range of fire weather. Implications of climate change, vegetation, and seasonal effects on fire behavior and the forest mosaic are discussed.

**Résumé** : Des simulations de feux printaniers et estivaux ont été réalisées à l'aide du Système canadien de prédiction du comportement des feux de forêts (FBP) et du système américain BEHAVE pour étudier le rôle de la végétation et des conditions météorologiques dans le comportement des feux en forêt boréale mixte. Les peuplements autour du lac Duparquet (Québec, Canada) ont été caractérisés comme feuillus, mixtes-feuillus, mixtes-conifères ou conifères selon le pourcentage de surface terrière coniférienne. La quantité des différents types de combustibles (litière, humus, débris ligneux, herbacées, et arbustes), et les conditions climatiques locales (trois niveaux de risque de feu) ont été entrées dans les modèles. Les variables prédites du comportement du feu sont la vitesse de propagation du front de flamme (ROS), l'intensité du front de flamme (HFI), et la surface brûlée. Les résultats de l'analyse statistique (ANOVA) montrent que les deux facteurs ne sont pas toujours significatifs et que qualitativement les systèmes attribuent différemment la variance expliquée par les deux facteurs: les conditions météorologiques sont le principal facteur intervenant dans le comportement du feu pour le FBP alors que la végétation occupe la première place avec BEHAVE. Cependant, trois feux prescrits réalisés en Ontario ont révélé que le système BEHAVE est inadéquat pour la région de la forêt boréale mixte alors que le FBP propose des prédictions quantitatives proches des valeurs réelles obtenues. Un indice forêt météo (IFM) extrême crée effectivement des feux très étendus et intenses, cependant des différences de comportement du feu selon les types de peuplements existent quel que soit l'IFM. L'impact des changements climatiques, de la composition de la végétationet de la saison sur le comportement du feu et sur la mosaïque forestière est discuté.

## Introduction

The boreal forest stretches across Canada and is a natural ecosystem affected by large-scale natural disturbances (Shugart et al. 1992), such as insect outbreaks (Blais 1983; Holling 1992; Morin 1994) and fires (Cogbill 1984; Johnson 1992; Levine et al. 1993; Pickett and White 1985; Turner and Romme 1994). The fire environment is composed of weather, fuels, and topography, and these three factors constantly interact (Agee 1997). However, the respective role of these factors may vary according to the region, the ecosystem type, and its historical events (Fryer and Johnson 1988; Harrington et al. 1991; Johnson 1992), through factors such as ignition probability (depending upon lightning and human

Received February 15, 2000. Accepted December 1, 2000. Published on the NRC Research Press Web site on March 2, 2001.

**C. Hély.**[1] University of Virginia, Department of Environmental Sciences, 291 McCormick Rd., Charlottesville, VA 22904 - 4123, U.S.A.
**M. Flannigan.** Natural Resources Canada, Canadian Forest Service, 5320 - 122 Street, Edmonton, AB T6H 3S5, Canada.
**Y. Bergeron.** Groupe de recherche en écologie forestière, Université du Québec à Montréal, C.P. 8888, Succursale Centre-Ville, Montréal, QC H3C 3P8, Canada.
**D. McRae.** Natural Resources Canada, Canadian Forest Service, P.O. Box 490, Sault Ste. Marie, ON P6A 5M7, Canada.

[1]Corresponding author (e-mail: chely@maddux.evsc.virginia.edu).

 DOI: 10.1139/cjfr-31-3-430 

population density), species composition, stand structure, and the climate conditions associated with each site (Harrington et al. 1991; Heinselman 1973; Pickett and White 1985; Shugart et al. 1992; Wein and Moore 1977). For example, Bessie and Johnson (1995) have shown that weather was the most important factor for fire occurrence in the western part of Canada. Bergeron and Archambault (1993) have shown that high fire frequency in the eastern Canadian mixedwood boreal forest was associated with longer drought periods in summer during the “Little Ice Age,” whereas low fire frequency was associated with moister summers. Different studies have found an increased risk of fire ignition and propagation as a result of long-term increases in fuel accumulation in several ecosystem types (Aber and Melillo 1991; Dodge 1972; Schimmel and Granström 1997; Wright and Bailey 1982). The composition differences among studied forest types may explain the differences of interpretations. The weather may become the most important factor where the forest mosaic composition is homogeneous or when fire frequency is low and fires occur under extreme weather conditions such as the blocking high pressure anomaly events (Flannigan and Harrington 1988). On the other hand, the vegetation composition may be the driving factor when fire frequency is high within a forest mosaic where the stand composition is quite variable. The mixedwood boreal forest is an interesting ecosystem for analyzing the effects of meteorological conditions and vegetation characteristics, because fire frequency is high and the vegetation composition is variable. Furthermore, knowledge of the respective role of these two factors is required in several applications, such as understanding if fire control policies have to be based on vegetation composition and if the fire cycles differ according to stand type.

The first objective of this study, then, is to evaluate the respective effects of vegetation characteristics and weather conditions on fire behavior in the mixedwood boreal forest. Both factors should be significant, but the vegetation (fuel) factor is most important. This hypothesis is based on species composition (particularly the presence of numerous deciduous and mixed stands) and the relationship between flammability and seasonal phenology changes (Van Wagner 1983) that exists in the mixedwood boreal forest. In this study, flammability is defined as the time spent in pyrolysis (Johnson 1992) and corresponds with the delay required for a particle exposed to a source of heat to be chemically decomposed before the ignition occurs. The delay ends with the occurrence of the flaming stage of combustion. The climatic conditions during the fire season also vary, but it may not be as important as the vegetation variability.

Among the tools that are available to assess the effects of meteorological conditions and vegetation characteristics, there are two fire behavior prediction systems used across North America. The first is the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992), an empirical model based on wildfire and prescribed burn data. This model is used to determine the behavior of surface and crown fires. The second is the BEHAVE system developed for the Unites States (Andrews 1986; Andrews and Chase 1989; Burgan and Rothermel 1984), which is a deterministic model that is based on the physical properties of fuels studied in the laboratory rather than on field data. The BEHAVE system is only used to determine surface fire behavior. Both models were built to predict fire behavior and to help understand the effects of fire on the different ecosystem compartments. The systems give as primary outputs the rate of spread of the fire front (ROS) and the head fire intensity (HFI), which, combined together, can determine the fire severity. In this study, fire severity refers to the impact of fire on the ecosystem through fuel consumption and the fire-caused vegetation mortality. A secondary output variable is the burned area for an elapsed time since fire ignition, which forest managers can use to estimate the potential patch size of expected burned stands. It should be noted, however, that these two prediction systems use several inputs with varying definitions within the fire environment, which could result in different fire behavior predictions.

The second objective of this study is to compare the two national fire behavior prediction systems (FBP and BEHAVE). First, we will compare the two systems using the results obtained for spring and summer simulations using fuel inventories of 48 sampled stands and six weather conditions, corresponding to three fire-risk levels. Secondly, we will use independent data sets obtained from three research burns conducted in the mixedwood boreal forest of Ontario (D.J. McRae, personal communication). We will compare the surface fire behavior components recorded during the research burns with predicted fire behavior sets from the two systems, using fuel inventories and weather conditions that were observed during these fires. The BEHAVE system should give more realistic predictions because it is based on measured fuel loading, whereas the FBP System defines the fuel type according to a small number of discrete stand types.

## Materials and methods

### Fire behavior prediction systems background

*The FBP System*

Detailed information about the Canadian Forest Fire Danger Rating System and its subsystems the Canadian Forest Fire Weather Index (FWI) and the FBP systems can be found in Canadian Forestry Service (1987), Forestry Canada Fire Danger Group (1992), and Hirsch (1996). The FWI and FBP subsystems relate to the relative wildland fire potential and the actual fire behavior, respectively. The FBP System has 16 general fuel types, which represent many, but not all, of the major fuel types found in Canada (Hirsch 1996). For the weather inputs, the FBP System uses the Fine Fuel Moisture Code (FFMC), the Initial Spread Index (ISI), and the Buildup Index (BUI) from the FWI System. These indexes are considered as fuel moisture codes and fire behavior indexes, and they are calculated from 12:00 local standard time observations of temperature, relative humidity, wind speed, and precipitation for the previous 24 h. The third fire environment factor is topography and it can be characterized using percent slope and aspect.

*The BEHAVE system*

The BEHAVE system is made up of two subsystems: the fuel modeling system referred to as FUEL (Burgan and Rothermel 1984) and the fire behavior prediction subsystem BURN, with FIRE1 and FIRE2 programs (Andrews 1986; Andrews and Chase 1989). The FUEL subsystem provides 13 standard existing fuel models that can be used unaltered or modified to create new fuel

**Table 1.** Weather data and fire weather indexes for the six selected weather days from local meteorological stations around Lake Duparquet.

| Replicate | Day | Temperature (°C) | Relative humidity (%) | Wind speed (km/h) | FFMC | ISI | BUI | FWI | Fire weather class |
|---|---|---|---|---|---|---|---|---|---|
| 1 | *D* – 1 | 30 | 18 | 21 | | | | | |
| | *D* | 30 | 24 | 9 | 87.4 | 4.6 | 11.5 | 5 | Low |
| 2 | *D* – 1 | 19 | 76 | 6 | | | | | |
| | *D* | 26 | 53 | 9 | 72.7 | 1.1 | 76.7 | 5 | Low |
| 1 | *D* – 1 | 14 | 36 | 3 | | | | | |
| | *D* | 16 | 35 | 22 | 89.0 | 11.5 | 15.1 | 15 | Moderate |
| 2 | *D* – 1 | 28 | 59 | 5 | | | | | |
| | *D* | 29 | 65 | 5 | 86.8 | 3.4 | 92.5 | 15 | Moderate |
| 1 | *D* – 1 | 22 | 14 | 7 | | | | | |
| | *D* | 23 | 14 | 9 | 95.4 | 14.1 | 40.4 | 25 | Extreme |
| 2 | *D* – 1 | 31 | 15 | 4 | | | | | |
| | *D* | 25 | 29 | 7 | 91.8 | 8.0 | 85.5 | 25 | Extreme |

**Note:** FFMC, Fine Fuel Moisture Code, is a numerical rating of the moisture content of litter and other cured fine fuels. This code is an indicator of the relative ease of ignition and flammability of fine fuel. ISI, Initial Spread Index, is a rating of the expected rate of fire spread. It combines the effects of wind and FFMC on rate of spread without the influence of variable quantities of fuel. BUI, Buildup Index, is a numerical rating of the total amount of fuel available for combustion. FWI, Fire Weather Index, a rating of fire intensity that combines ISI and BUI. It is suitable as a general index of fire danger throughout the forested areas of Canada (Canadian Forestry Service 1987). *D*, weather conditions used in BEHAVE; *D* – 1, weather conditions the day previous to the simulated day.

models based on the measured loading data for each fuel component. The SITE module in the FIRE1 program predicts rate of spread and frontal fire intensity, whereas the SIZE module in the FIRE1 program calculates the area burned from a point source that results in a rough elliptical shape. The weather and topography conditions are fully described inputs in the SITE module, which uses information included in the FUEL model file to provide the fire behavior prediction outputs.

## Relative importance of vegetation and weather on fire behavior

### *Study area*

The study area is located on the Lake Duparquet Research and Teaching Forest, found in the clay belt of northwestern Quebec (48°30′N, 79°20′W), a large physiographic region characterized by lacustrine clay deposits left by the proglacial lakes Barlow and Ojibway (Vincent and Hardy 1977). The area surrounding Lake Duparquet has forests that have never been commercially harvested. Lake Duparquet is situated at the southern limit of the boreal forest in the Missinaibi–Cabonga section (Rowe 1972), which is characterized by an association of balsam fir (*Abies balsamea* (L.) Mill.), black spruce (*Picea mariana* (Mill.) BSP), paper birch (*Betula papyrifera* Marsh.), white spruce (*Picea glauca* (Moench) Voss), and trembling aspen (*Populus tremuloides* Michx.). The mean annual temperature is 0.6°C, the mean annual precipitation is 822.7 mm, and the mean annual frost-free period is 64 days. However, freezing temperatures may occur throughout the year (Environment Canada 1993).

### *Data collection*

*Stands selection:* Forty-eight stands were selected on mesic clay deposits and gentle slope around Lake Duparquet. All were regenerated from stand-replacing fires, dating from 32 to 236 years ago (Bergeron 1991; Dansereau and Bergeron 1993). Each stand was inventoried using one 30-m sided equilateral sample triangle (McRae et al. 1979; Alberta Forest Service 1984) to evaluate all downed woody fuels. We sampled the stand structure (tree species, tree densities) using the point-centered quadrant method (McRae et al. 1979) with six sample points located along the triangle (Alberta Forest Service 1984), and the equations from Mueller-Dombois and Ellenberg (1974) to calculate tree densities. The 48 stands were characterized as being deciduous (D), mixed-deciduous (MD), mixed-coniferous (MC), or coniferous (C), if their conifer basal area was <25%, 25–50%, 51–75%, or >75% of stand basal area, respectively. The random sampling of stands to provide an accurate reflection of the landscape composition in this area resulted in 24 D, 13 MD, 4 MC, and 7 C stands.

*Fuel inventory:* For each stand, downed woody fuels were measured by the line intersect method (Van Wagner 1968) along the equilateral triangle (McRae et al. 1979), as to measure all pieces from diameters <0.5 cm to big branches and boles with diameters >7 cm. We first used the five classes recommended by McRae et al. (1979). We then used a linear interpolation to split these diameter class loads from the five classes presented above to the three American classes: 1-h, 10-h, and 100-h time lag dead woody loads (Bradshaw et al. 1983). Shrub, herbs, and litter fuels (Brown et al. 1982) were measured in quadrats that were evenly spaced along the 90-m triangle transect. The basal diameter of shrubs (by species) was measured in nine quadrats (1 $m^2$) at 10-m intervals. Loads were calculated from equations determined from shrub samples collected in the Duparquet area (I. Aubin, personal communication). Shrub height and percentage of dead branches were also measured. Litter (L layer) and duff depths (F + H layers) were measured in 12 quadrats (0.0625 $m^2$ each) and their material was separated and collected to obtain their ovendried mass. The surface-fuel components to be used in the BEHAVE prediction system were divided into the following classes: litter, live shrubs and herbs, 1-, 10-, and 100-h time lag fuels (dead wood and dead shrubs when appropriate). Finally each fuel class was assigned a standard surface-area-to-volume ratio according to Burgan and Rothermel (1984).

*Weather data source:* All 12:00 local standard time weather data (temperature, precipitation for the previous 24 h, wind speed, and relative humidity) for the 1991–1997 period were obtained from four local weather stations set up around Lake Duparquet. From these data sets, we selected three fire weather classes (Table 1). To compare our weather classes with other Canadian references, the low fire weather class (FWC) corresponds to the average fire weather (FWI = 5) of the Canadian zones 3 and 4, where the study area is located.[2] The moderate (FWI = 15) and extreme (FWI = 25) fire weather classes selected have been previously used for prescribed burns in Ontario (Stocks 1987; Stocks et al. 1989). Because several combinations of intermediate FWI indexes (BUI, ISI) can result in the same final FWI, weather conditions from 2 days were selected from the observed data, corresponding with simultaneously minimum BUI and maximum ISI or the inverse (Table 1).

### *Simulation characteristics*

With respect to topography, a zero slope effect and an elevation of 300 m were used to represent conditions on the study area. The point-source ignition pattern was chosen to emulate natural fire ignitions. This pattern is automatically used in BEHAVE, whereas the FBP System provides options for using either a point source or a line as the ignition source pattern. The elapsed time since ignition for this study was fixed at 2 h to calculate the burned area (in hectares). Two hours was selected as the acceleration time required to reach the equilibrium state, which has been preliminary calculated with the FBP System. Indeed, among the 48 stands, the slowest acceleration took more than 1 h to reach the equilibrium state. We then decided that 2 h would be long enough for both systems to simulate a fire propagation at the equilibrium state for all stands.

Simulations using the two fire behavior prediction systems (FBP and BEHAVE) were run separately for all 48 stands using the six different weather condition days. Simulation was based on spring conditions when deciduous foliage is absent (M1 in the FBP System) and on summer conditions when foliage is present (M2 in the FBP System). The presence of overstory foliage is also requested in BEHAVE. To take into account the seasonality in the herb and shrub layer, we did not include this layer in spring simulations (except for stands with *Taxus canadensis* Marsh. (Canada yew) for which we included this shrub load), but we did include this layer in summer simulations. This design led to 576 simulations for each system. We recorded the fire front rate of spread (ROS, m/min), the frontal fire intensity at the fire's head (HFI, kW/m), and the area burned (ha) 2 h after the fire ignition to have a complete understanding of the fire behavior characteristics.

For the FBP simulations, the only variation among stands is the relative coniferous basal area, which must be estimated when using the FBP System.

For the BEHAVE simulations (Andrews 1986), three moisture contents of the time lag fuels, related to same daily weather conditions in the FWI and FPB systems, are needed. The 1-h time lag fuel moisture content was calculated from the MOISTURE module of the FIRE2 BURN subsystem (Andrews and Chase 1989), using the same weather data ($D$ – 1 and $D$ days) that have been selected for the FBP System. The 10-h time lag fuel moisture content was predicted from the equilibrium moisture content equation of the National Fire Danger Rating System (Bradshaw et al. 1983). This equation calculates the 10-h time lag fuel moisture content from the 1-h time lag fuel type. Finally, the 100-h time lag fuel moisture content was directly calculated in the SITE module of the FIRE1 BURN subsystem (Andrews 1986). The moisture content of living herb and shrubs was fixed arbitrarily at 100%, according to recommendations from Burgan and Rothermel (1984).

### *Analyses*

We analyzed the respective role of stand types and weather conditions using a two-way ANOVA design on rank scores (Conover and Iman 1981) with the GLM procedure (SAS Institute Inc. 1985). We tested both factor effects (fuel and weather) and their potential interaction. The explained variance was partitioned using the type III sum of squares. We also looked at the differences in the fire behavior variables among the four stand types and the three FWC values using a Kruskal–Wallis test followed by a Hsu's MCB test (JUMP 1989). Finally, using these last two tests, we analyzed the FBP outputs between the four stand types for each FWC taken individually.

### Fire behavior comparisons between research burns and predictions from simulations

### *Research burn data*

The research burns (Appendix) used in this study were conducted in the mixedwood boreal forest of Ontario (46°38′N, 83°25′W) between 1992 and 1998 (D.J. McRae, personal communication). They represent three of the 10 plots that have been selected to support fire behavior experiments. Plot size is 1 ha and stand structure characteristics are summarized in the Appendix, as there is quite a difference between plots even though they are located on the same site. According to the weather conditions, plots 1 and 2 were burned under an FWI of 23 and 21, respectively, whereas the plot 3 burned with an FWI of 16.

Fire behavior simulations were conducted using the two prediction systems to compare the observed and predicted results, and to enable us to determine if a system is realistic in simulating fire behavior for this region of the boreal forest. According to the Appendix, plots 1 and 3 are considered as mixed-conifer stands while plot 2 is a coniferous stand. We conducted only spring fire simulations because all three burns occurred during spring.

### *Analyses*

We used the total time spent by the fire front to burn the entire plot area to calculate the mean ROS. Secondly, total fuel consumption (McRae et al. 1979) was calculated from the depth of burn measurements and fuel loading. The total heat release was then calculated from the fuel consumption and the low heat of fuel combustion for each fuel type. Finally, total heat release and ROS were used to calculate the frontal fire intensity. We then compared the observed results from the research burns with the predicted results from the two simulation systems.

## Results

### Relative importance of vegetation and weather on fire behavior

The results from the two-way ANOVA on the simulated output variables (ROS, HFI, and burned area) for spring and summer simulated fires with both the FBP and the BEHAVE systems are presented in Table 2. All overall tests are highly significant, but both factors are not always significant. The partitioning of the explained variance presents differences between the FBP and BEHAVE systems and between spring and summer fire behavior. The FBP System takes into account only one significant interaction between the two factors, but this interaction accounts for less than 3% of the total explained variance. Both factors are significant for the FBP System, but the maximum explained variance is always attributed to the weather, and the importance of weather decreases from the spring to the summer fire simulations. For spring ROS and burned-area variables, the importance of weather is about nine times greater than that of the vegetation factor, whereas in summer simulations, the importance of weather is only four to five times greater than that of the vegetation factor. For the HFI variable, the importance of weather is four times greater than that of the vegetation factor for both seasons. For BEHAVE simulations, vegetation is the only significant factor for HFI and burned area for both

[2] Simard, A.J. 1973. Forest fire weather zones of Canada. Environ. Can., Can. For. Serv., Ottawa, Ont. Map with text.

**Table 2.** Results of the two-way ANOVA realized on ranks for the simulated rate of spread, head fire intensity, and area burned for spring and summer fires in two simulations.

| | | Spring fire | | | Summer fire | | |
|---|---|---|---|---|---|---|---|
| Simulation | Variable[a] | *F* | *p* | Variance partition (%) | *F* | *p* | Variance partition (%) |
| **Rate of spread** | | | | | | | |
| FBP System | Overall model | 171.25 | 0.0001 | | 126.37 | 0.0001 | |
| | Stand type | 27.86 | 0.0001 | 9.76 | 47.82 | 0.0001 | 22.71 |
| | FWC | 286.34 | 0.0001 | 90.24 | 244.19 | 0.0001 | 77.29 |
| BEHAVE | Overall model | 4.77 | 0.0003 | | 5.87 | 0.0001 | |
| | Stand type | 4.42 | 0.0041 | 56.87 | 7.31 | 0.0001 | 74.73 |
| | FWC | 5.14 | 0.0064 | 41.13 | 3.71 | 0.0258 | 25.27 |
| **Head fire intensity** | | | | | | | |
| FBP System | Overall model | 64.68 | 0.0001 | | 106.63 | 0.0001 | |
| | Stand type | 41.25 | 0.0001 | 24.04 | 46.84 | 0.0001 | 26.36 |
| | FWC | 188.78 | 0.0001 | 73.37 | 196.31 | 0.0001 | 73.64 |
| | Stand type × FWC | 2.22 | 0.0413 | 2.59 | | | |
| BEHAVE | Overall model | 11.8 | 0.0001 | | 18.54 | 0.0001 | |
| | Stand type | 18.96 | 0.0001 | 100 | 29.7 | 0.0001 | 100 |
| | FWC | 1.07 | 0.3445 | 0 | 1.8 | 0.1669 | 0 |
| **Burned area** | | | | | | | |
| FBP System | Overall model | 208.9 | 0.0001 | | 132.31 | 0.0001 | |
| | Stand type | 24.7 | 0.0001 | 7.09 | 43.74 | 0.0001 | 19.83 |
| | FWC | 485.19 | 0.0001 | 92.91 | 265.17 | 0.0001 | 80.17 |
| BEHAVE | Overall model | 4.5 | 0.0006 | | 8.45 | 0.0001 | |
| | Stand type | 6.59 | 0.0003 | 100 | 12.51 | 0.0001 | 100 |
| | FWC | 1.37 | 0.2553 | 0 | 2.37 | 0.0954 | 0 |

**Note:** *F* tests and associated probabilities are given. The explained variance was partitioned between factor using the type III sum of squares.
[a]FWC, fire weather class.

spring and summer simulations. For ROS, both factors are significant, but the vegetation factor is the most important, and the percentage of variance explained by vegetation increases from the spring to the summer fires. The change in the partitioning of the variance among the two factors from spring to summer simulations could result from seasonal variation related to the emergence of understory foliage.

### Differences in the fire behavior variables among the four stand types and the three FWC values

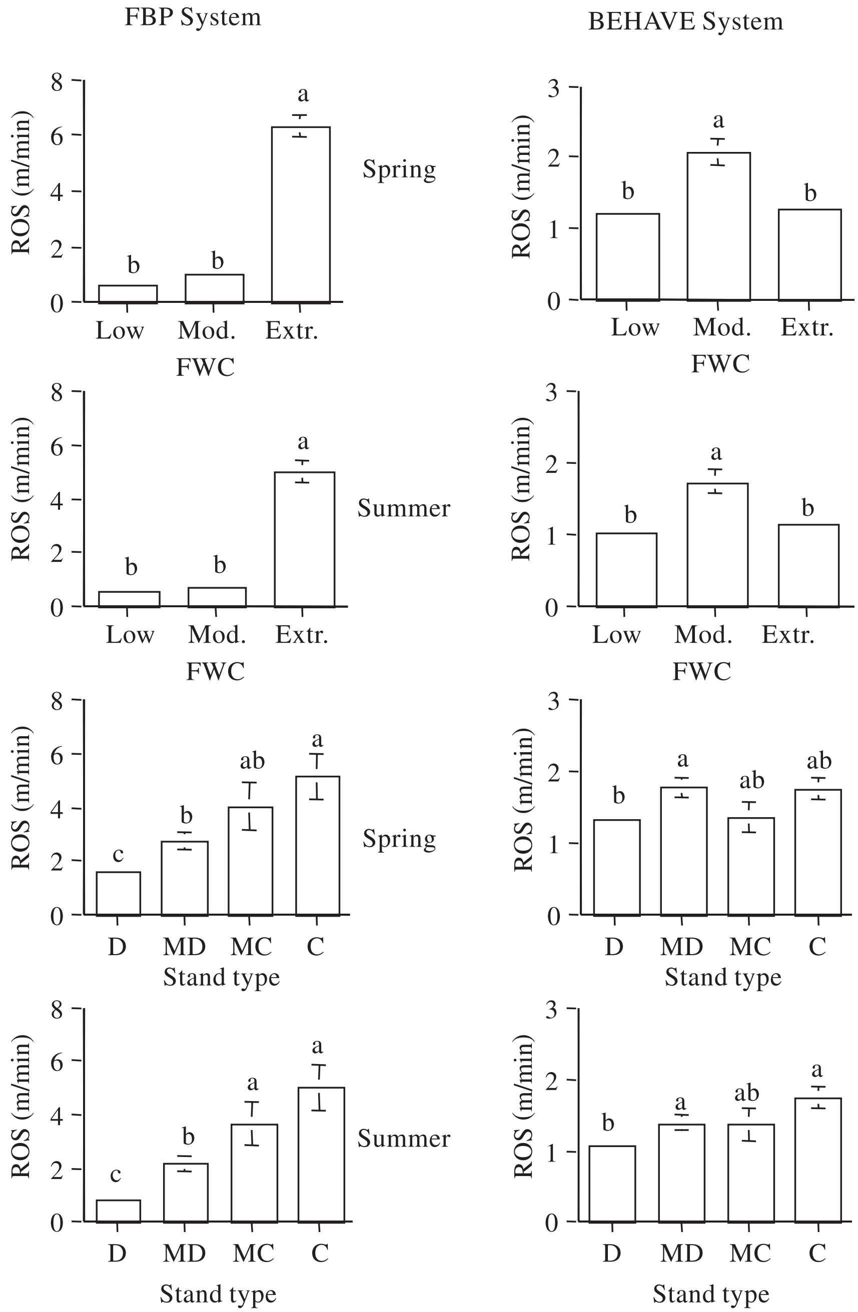
Differences for ROS, HFI, and burned area among stand types and FWC are presented in Figs. 1, 2, and 3, respectively. These figures present the spring and summer fire simulations for both systems. The first item of note is the difference in value ranges between both systems for a given variable; the quantitative outputs from the FBP System are always higher than those from BEHAVE. The three figures will be analyzed together because they present the same trends for each season and each system.

For the weather factor, the FBP System shows that the three fire behavior variables (ROS, HFI, and burned area) have the highest significant values with the extreme FWC for both seasons. Significant differences between the low and moderate FWC only exists for the summer burned area. For BEHAVE, predicted ROS is the only variable that shows significant difference among FWC, with the moderate FWC creating the fastest ROS (twice as high as for other FWC) for both seasons. For both systems, spring fire behavior always presents faster ROS, higher HFI, and larger areas burned than those in summer simulation.

For the vegetation factor (stand types), the FBP presents significant differences among the four stand types for the HFI variable. There is no significant difference between mixed-coniferous (MC) and mixed-deciduous (MD) or coniferous (C) stands for ROS, nor between deciduous (D) and MD stands for the burned-area variable. In all cases, the highest values for the three variables are recorded for C stands; the values then decrease from the C to the D stands with mixed stands at an intermediate position. BEHAVE presents significant differences between D and C stands for spring HFI and all summer predictions, whereas there is no significant difference between the two mixed stands types. In all cases and for both systems, summer fire behavior is also less important than spring fire behavior.

The comparisons of the fire behavior components (ROS, HFI, and burned area) predicted by the FBP System between the four stand types for each FWC and two seasons are reported in Table 3. These comparisons show that only three of the 18 models are not able to differentiate the four stand types (i.e., spring ROS for low FWC, spring and summer HFI for moderate FWC). In the 15 significant models, there is always a decreasing response to the fire behavior components, from coniferous stands that show the highest values to deciduous stands that are characterized by the lowest values. Several models show differences between deciduous, mixed, and coniferous stands, without showing differences between the two mixed types. Moreover, eight models (the best ones) significantly differentiate the four stand types, with two models dealing with the low FWC (spring and summer HFI) and six models dealing with the extreme FWC (ROS, HFI,

**Fig. 1.** Differences in the simulated rates of spread (ROS) between the FBP and BEHAVE systems for spring and summer fires according to the stand types (D, deciduous; MD, mixed-deciduous; MC, mixed-coniferous; C, coniferous) and the fire weather classes (FWC). Error bars are standard errors. Values with same letter are not significantly different at α = 0.05 for the Hsu's test.




and burned area both in spring and summer). According to these results, the idea that extreme fire weather will cause all vegetation types to burn comparably is not applicable to mixedwood boreal forests.

### Comparisons of the simulated and prescribed burns

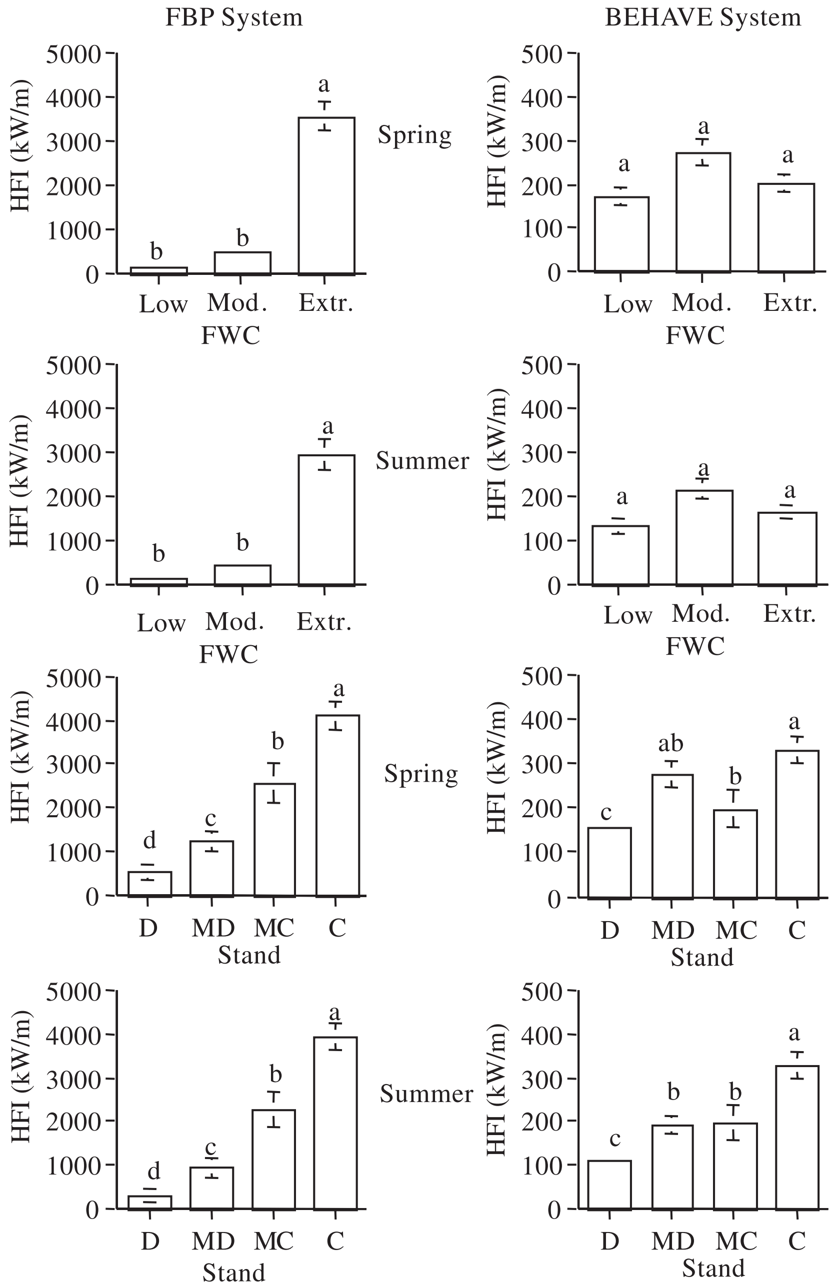
The fire behavior characteristics from the research burns and from the two simulation systems are reported in Table 4. The limited number of plots restricts us from conducting statistical tests for the purpose of comparisons, but the values alone show that for the three fire behavior variables the FBP predictions are closer to the observed fire behavior (and in the same order) than the BEHAVE predictions are. In fact, the BEHAVE quantitative predictions are so low for all components that a minimum threshold that would sustain the fire seems to not have been reached. The FBP System seems to overestimate the head fire intensity component, but research burns show that within the mixed-coniferous stand type (plots 1 and 3), fire behavior can be quite variable and likely explained by the FWI differences.

## Discussion

### Comparisons of the fire behavior prediction systems

By using different fire behavior prediction systems we have found that there are two kinds of responses: qualitative

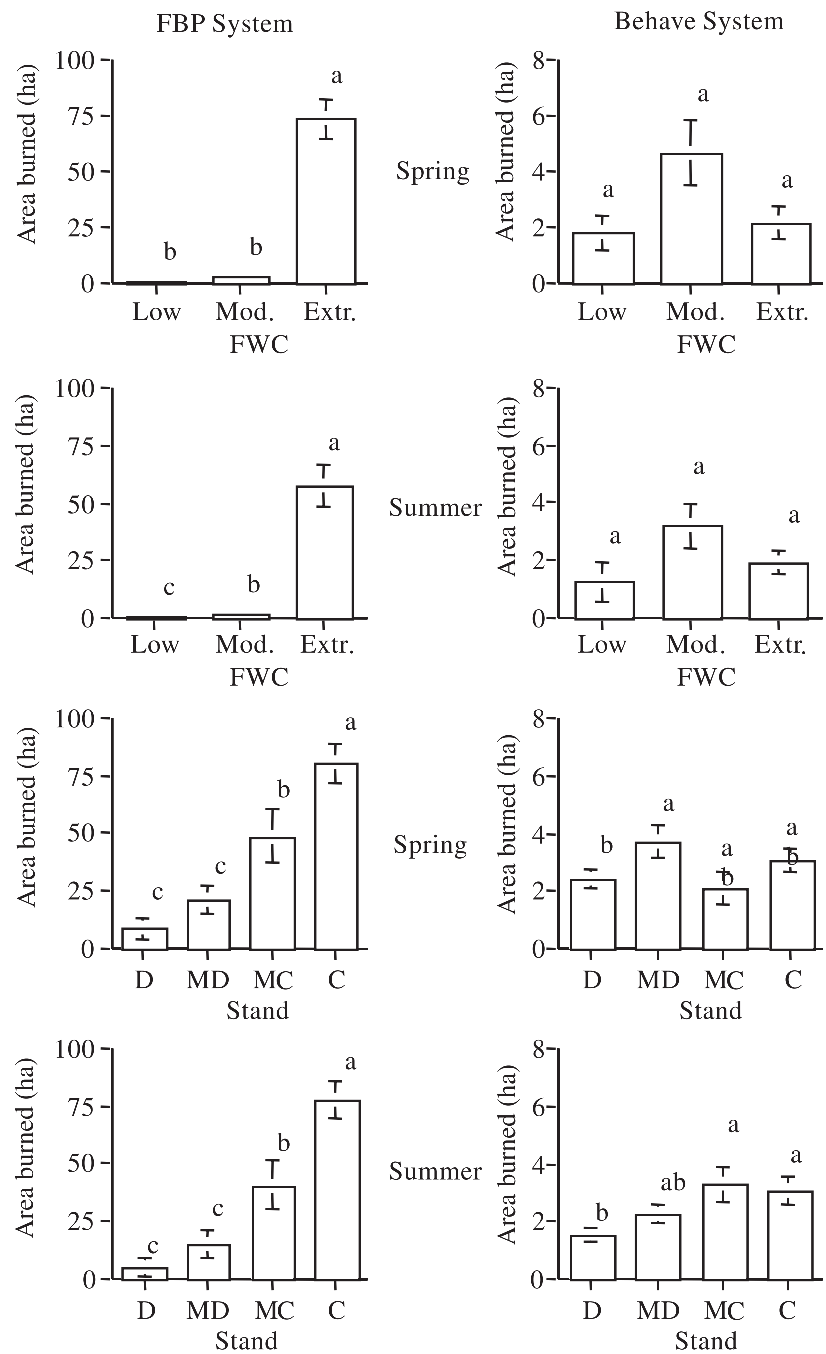
**Fig. 2.** Differences in the simulated head fire intensities (HFI) between the FBP and BEHAVE systems for spring and summer fires according to the stand types (D, deciduous; MD, mixed-deciduous; MC, mixed-coniferous; C, coniferous) and the fire weather classes (FWC). Values with same letter are not significantly different at α = 0.05 for the Hsu's test.




and quantitative. The qualitative response of the systems deals with the respective effects of the factors involved in the fire behavior predictions. For this qualitative aspect, the vegetation factor is significant in all simulations from the BEHAVE and the FBP systems, whereas the weather factor is not significant for the HFI and burned area predicted from BEHAVE. Moreover, the two systems assign different roles to these factors: in the FBP System, weather is the most important factor, whereas BEHAVE mainly attributes the explained variance to the vegetation factor. The quantitative response of the systems involves predictions of fire behavior components such as ROS, HFI, and burned area. The comparisons between the observed (research burns) and predicted (FBP and BEHAVE) fire behavior revealed that the FBP predictions were very close to the observed values, whereas the BEHAVE predictions were so low (HFI < 10 kW/m for the two plots) that they would correspond to smoldering fires in deep organic layers (Van Wagner 1983). In fact, BEHAVE seems to not achieve a minimum threshold beyond which fire propagation could be sustained.

Among weather and vegetation factors, only vegetation could explain the differences found between the two systems. Even though precipitation is included differently into both systems, it cannot discriminate between them. Indeed, while the FBP System records the amount of rain for the last 24 h and distributes it within different compartments through

**Fig. 3.** Differences in the simulated areas burned between the FBP and BEHAVE systems for spring and summer fires according to the stand types (D, deciduous; MD, mixed-deciduous; MC, mixed-coniferous; C, coniferous) and the fire weather classes (FWC). Values with same letter are not significantly different at α = 0.05 for the Hsu's test.




indexes, BEHAVE records only the duration of rain and allocates it only to the top portion of the exposed aboveground fuels for which moisture content reacts faster than the Duff Moisture Code (DMC) and Drought Code (DC) from the FWI System (Van Wagner 1975). Moreover, rain effects in BEHAVE cannot readily wet the fuels to near saturation as in the FWI and FBP systems (Van Wagner 1975). The FWI then has a longer record of precipitation through the DMC and the DC indexes than BEHAVE. Nevertheless, these facts would support higher fire behavior for BEHAVE because fuels would dry faster than for the FBP, but this is not the case. Wind speed does not seem to discriminate between both systems because Kruskal–Wallis tests performed on fire behavior predictions for the moderate FWC have shown the same significant difference results. Indeed, for this moderate FWC, the wind speed differs between the 2 days (22 and 5 km/h for the first and the second replicates, respectively). The comparisons have shown (not presented) that both systems predicted significantly higher outputs ($p < 0.01$) for the windy day than for the light-wind day. The most likely explanation for the differences between the two systems and the low quantitative predictions from BEHAVE

**Table 3.** Comparisons between the different stand types for each fire weather class (FWC) and each fire behavior component for spring and summer FBP simulations.

| Fire behavior components | FWC | Deciduous | Mixed-deciduous | Mixed-coniferous | Coniferous |
|---|---|---|---|---|---|
| **Spring fires** | | | | | |
| ROS (m/min) | Low | 0.38 ± 0.04*a* | 0.67 ± 0.08*b* | 1.03 ± 0.23*ab* | 1.31 ± 0.21*a* |
| | Mod. | 0.70 ± 0.04*a* | 1.01 ± 0.11*a* | 1.40 ± 0.36*a* | 1.77 ± 0.35*a* |
| | Ext. | 3.88 ± 0.25*d* | 6.53 ± 0.34*c* | 9.73 ± 0.62*b* | 12.45 ± 0.47*a* |
| HFI (kW/m) | Low | 63.00 ± 3.00*d* | 143.31 ± 6.03*c* | 271.45 ± 17.19*b* | 413.43 ± 17.28*a* |
| | Mod. | 227.12 ± 29.32*a* | 486.22 ± 90.06*a* | 911.20 ± 332.15*a* | 1 451.00 ± 393.34*a* |
| | Ext. | 1320.20 ± 112.50*d* | 3064 ± 152.86*c* | 6513.90 ± 275.57*b* | 10 512.60 ± 208.31*a* |
| Burned area (ha) | Low | 0.23 ± 0.06*c* | 0.69 ± 0.15*bc* | 1.50 ± 0.60*ab* | 2.36 ± 0.67*a* |
| | Mod. | 1.27 ± 0.11*b* | 2.81 ± 0.46*b* | 5.75 ± 2.05*a* | 8.21 ± 2.04*a* |
| | Ext. | 23.30 ± 7.09*d* | 59.85 ± 9.63*c* | 138.9 ± 17.36*b* | 231.3 ± 13.13*a* |
| **Summer fires** | | | | | |
| ROS (m/min) | Low | 0.22 ± 0.03*c* | 0.56 ± 0.07*b* | 0.94 ± 0.22*a* | 1.29 ± 0.21*a* |
| | Mod. | 0.34 ± 0.04*c* | 0.73 ± 0.11*b* | 1.16 ± 0.39*ab* | 1.58 ± 0.38*a* |
| | Ext. | 2.09 ± 0.24*d* | 5.29 ± 0.33*c* | 8.96 ± 0.60*b* | 12.21 ± 0.45*a* |
| HFI (kW/m) | Low | 37.34 ± 3.23*d* | 119.46 ± 6.13*c* | 253.43 ± 17.01*b* | 406.11 ± 18.04*a* |
| | Mod. | 127.12 ± 21.06*a* | 388.32 ± 79.27*a* | 833.25 ± 317.13*a* | 1 357.29 ± 376.03*a* |
| | Ext. | 733.60 ± 116.79*d* | 2332.51 ± 158.72*c* | 5724.57 ± 286.08*b* | 10 137.17 ± 216.26*a* |
| Burned area (ha) | Low | 0.00 ± 0.00*c* | 0.50 ± 0.11*bc* | 1.38 ± 0.53*b* | 2.36 ± 0.67*a* |
| | Mod. | 0.27 ± 0.08*c* | 1.65 ± 0.38*bc* | 4.75 ± 1.89*b* | 9.00 ± 2.56*a* |
| | Ext. | 8.10 ± 6.62*d* | 42.75 ± 8.99*c* | 115.9 ± 16.21*b* | 221.54 ± 12.26*a* |

**Note:** ROS, rate of spread; HFI, head fire intensity; mod., moderate; ext., extreme. Values are means ± SE. Values in a row followed by the same letter are not significantly different at $\alpha = 0.05$ for the Hsu's test.

**Table 4.** Values for the fire behavior components from the research burns and from the two simulation systems.

| Fire behavior components | Plot 1 | Plot 2 | Plot 3 |
|---|---|---|---|
| **Research burns** | | | |
| ROS (m/min) | 8.84 | 12.86 | 3.72 |
| HFI (kW/m) | 2236 | 3420 | 789 |
| Area burned (ha) | 1 | 1 | 1 |
| **FBP predictions** | | | |
| ROS (m/min) | 8.51 | 11.65 | 7.17 |
| HFI (kW/m) | 3538 | 7522 | 1939 |
| Area burned (ha) | 1.04 | 0.99 | 4.94 |
| **BEHAVE predictions** | | | |
| ROS (m/min) | 1.00 | <0.1 | <0.1 |
| HFI (kW/m) | 121 | 15 | 12 |
| Area burned (ha) | <0.01 | <0.01 | <0.01 |

**Note:** ROS, rate of spread; HFI, head fire intensity.

could come from the vegetation factor, and more specifically from the fact that BEHAVE does not take into account the deeper duff layer. Indeed, the research burns have shown that the average depth of burn was deeper than the 0.5-cm litter layer. This could support the idea that the fuel amounts in BEHAVE would be underestimated and not recognized in supporting fire propagation. This would lead to low or unsustainable ROS, HFI, and burn area, as shown by the results. The FBP System, on the other hand, takes implicitly into account the humus layer down to the deep duff. Finally, BEHAVE does not allow crowning whereas the FBP System does. Results from the FBP have shown that the first two experimental burns were under intermittent crown fire conditions.

## Role of vegetation and weather factors

The importance of the vegetation and weather factors depends on the fire behavior prediction system used (as shown in this study) and on the studied region. Fires, in general, are more frequent and more severe in the western part of the Canadian boreal forest than in the eastern part, where the climate is moister and less favorable to wildfire propagation. Moreover, while boreal forest types are more segregated in western Canada, where aspen dominates the plains and conifers dominates the foothills, mixedwood forest types containing both conifer and hardwood species are more common in eastern Canada (Bergeron and Dubuc 1989; Bergeron and Dansereau 1993). Studying the relative importance of vegetation composition and weather conditions on fire behavior in the western Canadian subalpine forest, Bessie and Johnson (1995) have found by using only BEHAVE that the weather was the most important factor explaining fire behavior. In their study, the vegetation is only composed of conifer species, all being good fuels to burn. Therefore, the warmer and drier western climate could be the real driving factor because the weather variability has always been higher than the vegetation variability. Conversely, our study shows that in the eastern Canadian mixedwood boreal forest the use of BEHAVE would lead us to present a different conclusion, with the vegetation factor being the most important one for ROS, and the only significant factor for HFI and area burned. The presence of deciduous species, less prone to burn as compared with conifer species (Brown and Davis 1973), would induce higher vegetation variability than weather variability; therefore, vegetation composition could be the most important factor in fire behavior for eastern Canadian mixedwood boreal forests. At best, future fire behavior studies should acknowledge the regional natural variability that exists over the continent in terms of climate and vegetation composition (Forestry Canada Fire Danger Group 1992; Harrington et al. 1991; Shugart et al. 1992). Different vegetation types and weather conditions interact together with the topography to create unique fire environments. It is important, then, to consider all environmental factors that interact with fire behavior (Agee 1997) before regionally adapting the relevant model (i.e., the FBP for the mixedwood boreal forest of eastern Canada) to find out the potential dominating factors. In steep slope regions, topography could be as much of a driving factor as fuel type or weather because the slope is known to have important effects on ROS and on the size and shape of burned patches (Andrews 1986; Forestry Canada Fire Danger Group 1992; Fryer and Johnson 1988; Jean 1992; Johnson 1992).

If the FBP System is chosen as the relevant model for the mixedwood boreal forest of eastern Canada, both vegetation and weather factors have a significant effect, but weather is the most important factor because it explains the maximum of the variance (Table 2). Nevertheless, the vegetation factor has a significant influence on fire behavior components whatever the FWC conditions (Table 3). This shows that the small amount of explained variance attributed to the vegetation factor could, however, correspond to a more important effect of stand type on fire behavior. Moreover, the natural stand variability is higher in the studied forest mosaic than shown in the analyses, and it could have a greater influence on fire behavior. Indeed, stands with *Picea mariana* or *Pinus banksiana* Lamb. on exposed bedrock, or with *Larix laricina* (Du Roi) K. Koch or *Fraxinus nigra* Marsh. on silted lowland sites subject to flooding and boggy habitats, respectively (Bergeron and Dubuc 1989), are present in the patchiness of the forest mosaic but were not included in the study. The idea that slight differences between forest stands in fuel characteristics are insignificant when compared with the large, short-term variations in the weather (Johnson 1992) should not be applied, at least to the mixedwood boreal forest. The same is true of the idea that above a certain extreme fire weather risk, all vegetation types will burn similarly. Our results show that deciduous dominated stands would support less intense fires, which would burn smaller areas than fire in conifer dominated stands. Several studies dealing with large burned areas (Johnson 1992; Payette 1992; Van Wagner 1983) reported conifer forest mosaics such as the black spruce – feathermoss forest where the deciduous species and stands are poorly represented. However, a recent study (Bergeron et al. 1999) has shown that fires burning large areas were proportionately more numerous in the black spruce – feathermoss forest than in the mixedwood boreal forest, and this despite similar regional climatic conditions (Hofgaard et al. 1999). These results are consistent with ours, and they show that the conifer composition may have a direct effect on the area burned at the stand and the landscape level. Also, the head fire intensity increases with an increase in the conifer proportion. Therefore, fires in conifer stands or in landscape mosaics dominated by conifer stands should also be more severe.

The fire season is another important factor to take into account. The ANOVA results have shown that season does not change the order of importance of the two factors, but it generally increases the vegetation influence during summer simulations. Moreover, the seasonal factors are responsible for lower fire behavior values recorded in the summer simulation than in spring. The higher the deciduous percentage, the higher spring and summer differences. However, the only difference recorded between spring and summer pertains to the vegetation factor, namely the presence or absence of the deciduous fuel type (Forestry Canada Fire Danger Group 1992). In spring, the absence of deciduous tree and herbaceous foliage does not interfere with the ground and surface fuel bed warming from the direct sunlight (Furyaev et al. 1983), whereas in summer deciduous leaves intercept the sunlight and create cooler and moister understory and ground environments (Van Wagner 1983). This explains the slower ROS in summer associated with lower intensities and smaller burned areas. Generally, conifer stands in this region are older and present a more open canopy than deciduous stands. Because these conifer species are evergreen, there will be little or no difference between spring and summer foliage or between the seasonal fire behavior as shown by the mixed-coniferous and coniferous stands. When a seasonal difference exists, it is due to the presence of a herb cover in summer, which retains a higher moisture content in the surface fuels and decreases the propagation rate. This ground cover does not take into account a moss layer, since this fuel type does not exist in these stand types (De Grandpré et al. 1993). In this way, deciduous phenological changes explain the increased importance of the vegetation factor for summer fires through the indirect season factor. Wotton and Flannigan (1993) have shown that global warming may lead to an increase in the length of the fire season, and this may have some consequences on the number and size of fires during the fire season. Indeed, the fire season would start earlier because many stands would still be leafless, and it would end later because stands with senescent foliage provide good conditions for fire propagation.

## Conclusion

This research has shown the importance of considering all the environmental factors of fire before selecting the appropriate fire behavior prediction system for any given area. The use of prescribed burns, when available, can be helpful to choose the best system. The BEHAVE system is not well adapted to the mixedwood boreal forest to predict realistic quantitative fire behavior, whereas the FBP System seems to be an efficient fire behavior prediction system for this boreal ecosystem. The slight overestimation of the head fire intensity prediction from the FBP System should be improved by the adjustment of the model through the use of future prescribed burn data. Differences in fire behavior according to the stand composition are significant for all fire behavior variables (ROS, HFI, and burned area). This implies that the mixedwood boreal forest, with its natural stand variability in terms of conifer proportion, is a complex ecosystem in regards to fire disturbance. This ecosystem can indeed present several fire behaviors at the local scale. This inherent variability needs to be integrated in any fire behavior prediction system that aims to predict final size and shape of wildfires at the landscape level.

## Acknowledgements

This research was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC), le ministère de l'Éducation du Québec (Fonds pour la formation des chercheurs et l'aide à la recherche program), and the Network of Centres of Excellence in Sustainable Forest Management. We thank Marty Alexander for valuable advice on the use of the FBP System. We thank the members of the Groupe de recherche en écologie forestière interuniversitaire and staff of the Northern Forestry Centre in Edmonton for their help, and Brenda Laishley for editing.

## References

Aber, J.D., and Melillo, J.M. 1991. Terrestrial ecosystems. Saunders College Publishing, New York.

Agee, J.K. 1997. The severe weather wildfire—too hot to handle? Northwest Sci. **71**(1): 153–156.

Alberta Forest Service. 1984. Measurement and description of fuels in natural stands in Alberta. Alberta Forest Service, Edmonton, Alberta. Unnumbered Handb.

Andrews, P.L. 1986. BEHAVE: fire behavior prediction and fuel modeling system—BURN subsystem. Part 1. U.S. Dep. Agric. For. Serv. Interm. For. Range Exp. Stn. Tech. Rep. INT-194.

Andrews, P.L., and Chase, C.H. 1989. BEHAVE: fire behavior prediction and fuel modeling system—BURN subsystem. Part 2. U.S. Dep. Agric. For. Serv. Interm. For. Range Exp. Stn. Tech. Rep. INT-260.

Bergeron, Y. 1991. The influence of island and mainland lakeshore landscapes on boreal forest fire regimes. Ecology, **72**(6): 1980–1992.

Bergeron, Y., and Archambault, S. 1993. Decreasing frequency of forest fires in the southern boreal zone of Quebec and its relation to global warming since the end of the "Little Ice Age." Holocene, **3**(3): 255–259.

Bergeron, Y., and Dansereau, P.R. 1993. Predicting the composition of Canadian southern boreal forest in different fire cycles. J. Veg. Sci. **4**: 827–832.

Bergeron, Y., and Dubuc, M. 1989. Succession in the southern part of the Canadian boreal forest. Vegetatio, **79**: 51–63.

Bergeron, Y., Gauthier, S., Carcaillet, C., Flannigan, M.D., Prairie, Y., and Richard, P.J.H. 1999. Variability in fire frequency and forest composition in Canada's southeastern boreal forest: a challenge for sustainable forest management. *In* Proceedings of the Sustainable Forest Management Network Conference: Science and Practice: Sustaining the Boreal Forest, 14–17 Feb. 1999, Edmonton, Alta. Sustainable Forest Management Network, Edmonton, Alta. pp. 74–80.

Bessie, W.C., and Johnson, E.A. 1995. The relative importance of fuels and weather on fire behavior in subalpine forest. Ecology, **76**(3): 747–762.

Blais, J.R. 1983. Trends in the frequency, extent and severity of spruce budworm outbreaks in eastern Canada. Can. J. For. Res. **13**: 539–547.

Bradshaw, L.S., Deeming J.E., Burgan, R.E., and Cohen, J.D. 1983. The 1978 National Fire Danger Rating System: technical documentation. U.S. Dep. Agric. For. Serv. Interm. For. Range Exp. Stn. Tech. Rep. INT-169.

Brown, A.A, and Davis, K.P. 1973. Forest fire: control and use. 2nd ed. McGraw-Hill, New York.

Brown, J.K., Oberheu, R.D., and Johnston, C.M. 1982. Handbook for inventorying surface fuels and biomass in the Interior West. U.S. Dep. Agric. For. Serv. Interm. For. Range Exp. Stn. Tech. Rep. INT-129.

Burgan, R.E., and Rothermel, R.C. 1984. BEHAVE: fire behavior prediction and fuel modeling system—FUEL subsystem. U.S. Dep. Agric. For. Serv. Interm. For. Range Exp. Stn. Tech. Rep. INT-167.

Canadian Forestry Service 1987. Canadian Forest Fire Danger Rating System: user's guide. Canadian Forestry Service Fire Danger Group, Canadian Forestry Service, Ottawa, Ont.

Cogbill, C.V. 1985. Dynamics of the boreal forest of the Laurentian highlands, Canada. Can. J. For. Res. **15**: 252–261.

Conover, W.J., and Iman, R.L. 1981. Rank transformations as a bridge between parametric and non-parametric statistics. Am. Stat. **35**(3): 124–129.

Dansereau, P.R., and Bergeron, Y. 1993. Fire history in the southern boreal forest of northwestern Quebec. Can. J. For. Res. **23**: 25–32.

De Grandpré, L., Gagnon, D., and Bergeron, Y. 1993. Changes in the understory of Canadian southern boreal forest after fire. J. Veg. Sci. **4**: 803–810.

Dodge, M. 1972. Forest fuel accumulation—a growing problem. Science (Washington, D.C.), **177**: 139–142.

Environment Canada. 1993. Canadian climate normals 1961–90. Canadian Climate Program, Environ. Can. Atmos. Environ. Serv. Downsview, Ont.

Flannigan, M.D., and Harrington, J.B. 1988. A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada (1953–80). J. Appl. Meteorol. **27**: 441–452.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. For. Can. Inf. Rep. ST-X-3.

Fryer, G.I., and Johnson, E.A. 1988. Reconstructing fire behavior and effects in a subalpine forest. J. Appl. Ecol. **25**: 1063–1072.

Furyaev, V.V., Wein, R.W., and MacLean, D.A. 1983. Fire influences in *Abies*-dominated forests. *In* The role of fire in northern circumpolar ecosystems. *Edited by* R.W. Wein and D.A. MacLean. Scope, **18**: 221–234.

Harrington, J., Kimmins, J., Lavender, D., Zoltai, S., and Payette, S. 1991. The effect of climate change on forest ecology in Canada. *In* Proceedings of the 10th World Forestry Congress, 17–26 Sept. 1991, Paris. École nationale du génie rural, des eaux et des forêts, Nancy, France. Rev. For. Fr. Spec. Issue. Vol. 2. pp. 49–58.

Heinselman, M.L. 1973. Fire in the virgin forest of the boundary waters Canoe Area, Minnesota. Quat. Res. **3**: 329–382.

Hirsch, K.G. 1996. Canadian Forest Fire Behavior Prediction (FBP) System: user's guide. Nat. Resour. Can. Can. For. Serv. North. For. Cent., Edmonton, Alta. Spec. Rep. 7.

Hofgaard, A., Tardif, J., and Bergeron, Y. 1999. Dendrometric response of *Picea mariana* and *Pinus banksiana* along a latitudinal gradient in the eastern Canadian boreal forest. Can. J. For. Res. **29**: 1333–1346.

Holling, C.S. 1992. The role of forest insects in structuring the boreal landscape. *In* A systems analysis of the global boreal forest. *Edited by* H.H. Shugart, R. Leemans, and G.B. Bonan. Cambridge University Press, Cambridge, U.K. pp. 171–191.

Jean, F. 1992. Modélisation du comportement du feu. Influence de la pente et de la charge d'une litière d'aiguilles de pin maritime. Institut national de la recherche agronomique. Avignon, France. PIF 9205.

Johnson, E.A. 1992. Fire vegetation dynamics: studies from the North American boreal forest. Cambridge University Press, Cambridge, U.K.

JUMP. 1989. Statistical visualization for the Macintosh. Version 2.0.4. SAS Institute Inc., Cary, N.C.

Levine, E.R., Ranson, K.J., Smith, J.A., Williams, D.L., Knox, R.G., Shugart, H.H., Urban, D.L., and Lawrence, W.T. 1993. Forest ecosystem dynamics: linking forest succession, soil process and radiation models. Ecol. Model. **65**: 199–219.

McRae, D.J., Alexander, M.E., and Stocks, B.J. 1979. Measurement and description of fuels and fire behavior on prescribed burns: a handbook. Can. For. Serv. Great Lakes For. Res. Cent. Sault Ste. Marie, Ont. Rep. O-X-287.

Morin, H. 1994. Dynamics of balsam fir forests in relation to spruce budworm outbreaks in the boreal zone, Québec. Can. J. For. Res. **24**: 730–741.

Mueller-Dombois, D., and Ellenberg, H. 1974. Aims and methods of vegetation ecology. Wiley, New York.

Payette, S. 1992. Fire as controlling process in the Northern American boreal forest. *In* A systems analysis of the global boreal forest. *Edited by* H.H. Shugart, R. Leemans, and G.B. Bonan. Cambridge University Press, Cambridge, U.K. pp. 144–169.

Pickett, S.T.A., and White, P.S. 1985. The ecology of natural disturbance and patch dynamics. Academic Press, New York.

Rowe, J.S. 1972. Forest regions of Canada. Environment Canada, Ottawa, Ont. Publ. 1300.

SAS Institute Inc. 1985. SAS user's guide: statistics, version 6 ed. SAS Institute Inc., Cary, N.C.

Schimmel, J., and Granström, A. 1997. Fuel succession and fire behavior in the Swedish boreal forest. Can. J. For. Res. **27**: 1207–1216.

Shugart, H.H., Leemans, R., and Bonan, G.B. 1992. A systems analysis of the global boreal forest. Cambridge University Press, Cambridge, U.K.

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

Stocks, B.J., Lawson, B.D., Alexander, M.E., Van Wagner, C.E., McAlpine, R.S., Lynham, T.J., and Dubé, D.E. 1989. Canadian Forest Fire Danger Rating System: an overview. For. Chron. **65**(4): 258–265.

Turner, M.G., and Romme, W.H. 1994. Landscape dynamics in crown fire ecosystems. Landsc. Ecol. **9**(1): 59–77.

Van Wagner, C.E. 1968. The line intersect method in forest fuel sampling. For. Sci. **14**: 20–26.

Van Wagner, C.E. 1975. A comparison of the Canadian and the American forest fire danger rating systems. Environ. Can. Can. For. Serv. Petawawa For. Exp. Stn., Chalk River, Ont. Inf. Rep. PS-X-59.

Van Wagner, C.E. 1983. Fire behavior in northern conifer forests and shrublands. *In* The role of fire in northern circumpolar ecosystems. *Edited by* R.W. Wein and D.A. Maclean. Scope, **18**: 65–81.

Vincent, J.S., and Hardy, L. 1977. L'évolution et l'extension des lacs glaciaires Barlow et Ojibway en territoire québecois. Géogr. Phys. Quat. **31**: 357–372.

Wein, R.W., and Moore, J.M. 1977. Fire history and rotations in the New Brunswick Acadian forest. Can. J. For. Res. **7**: 285–294.

Wotton, B.M., and Flannigan, M.D. 1993. Length of the fire season in a changing climate. For. Chron. **69**(2): 187–192.

Wright, H.A., and Bailey, A.W. 1982. Fire ecology. Wiley, New York.

## Appendix

**Table A1.** Characteristics of the research burn plots.

| Characteristics | Plot 1 | Plot 2 | Plot 3 |
|---|---|---|---|
| Density (trees/ha) | | | |
| Stand living density | 3148 | 2474 | 2242 |
| Stand living coniferous density | 2456 | 1659 | 1601 |
| Stand living deciduous density | 692 | 815 | 641 |
| Stand snag density | 88 | 15 | 6 |
| Basal area ($m^2$/ha) | | | |
| Stand living basal area | 23.17 | 22.4 | 29.59 |
| Stand living coniferous basal area | 11.87 | 17.66 | 19.08 |
| Stand living deciduous basal area | 11.3 | 4.74 | 10.51 |
| Tree conifer percentage based on BA | 51.23 | 78.83 | 64.48 |
| Stand type based on classification | MC | C | MC |
| Prescribed burning | | | |
| Time spent to burn 1 ha (min) | 16 | 11 | 38 |
| Total slash consumed (kg/$m^2$) | 0.35 | 0.24 | 0.08 |
| Total duff consumed (kg/$m^2$) | 0.43 | 0.59 | 0.56 |
| Total fuel consumed (kg/$m^2$) | 0.78 | 0.84 | 0.64 |
| Total heat release (kJ/$m^2$) | 14909 | 15785 | 11832 |
| Fire behavior | | | |
| Rate of spread (m/min) | 8.84 | 12.86 | 3.72 |
| Head fire intensity (kW/m) | 2236 | 3420 | 789 |

**Note:** BA, basal area; MC, mixed-coniferous; C, coniferous stands.