Modeling Tree Mortality Following Wildfire in the Southeastern Canadian Mixed-Wood Boreal Forest

Christelle Hély, Mike Flannigan, and Yves Bergeron

ABSTRACT. We modeled tree mortality three months after a wildfire in the mixed-wood boreal forest (Quebec, Canada) using data from 1963 trees in 36 stands burned under a wide range of fire behavior conditions during the 1997 Val Paradis fire. Stand composition influenced the char height: height of burn was lower in deciduous stands than mixed or coniferous stands. Analysis of species mortality rates revealed that *Populus tremuloides* Michx. was the least fire-resistant species, whereas *Picea mariana* Moench and *Pinus banksiana* Lamb. were the most resistant species. Efficient interactions for conifers exist between crown and cambial resistance to injury and fire behavior, as diameter at breast height (DBH), total tree height (TOTH), and mean bark thickness are characteristic variables throughout the fire behavior range. The best logistic regressions, relating probability of wildfire-induced mortality to morphology and fire variables, always entered char height (CH) at the first step of the stepwise procedure, followed by a morphological variable (DBH or TOTH). The Kappa coefficient used for model validations revealed that logistic regressions using morphologic and fire variables were very efficient as compared to logistic regressions based only on morphologic variables. Potential applications of these results by land managers are discussed. For. Sci. 49(4):566–576.

Key Words: Fire intensity, logistic regression, *Picea mariana*, *Pinus banksiana*, *Populus tremuloides*.

Fire is a major environmental factor in boreal forests (Johnson 1992, Flannigan 1993, Bergeron et al. 1999), but little published information exists on the pattern of tree mortality in these forest types. However, managers need the ability to predict fire-caused tree mortality for various objectives [e.g., post wildfire salvage (Ryan et al. 1988), and prescribed fire planning (Brown and Debyle 1987)].

Most published studies on tree mortality deal with coniferous species, such as *Pseudotsuga menziesii* (Ryan et al. 1988, Peterson and Arbaugh 1989, Keane et al. 1990), *Pinus ponderosa* (Thomas and Agee 1986, Ryan 1998, Keane et al. 1990, Swezy and Agee 1991, Harrington 1993, Regelbrugge and Conard 1993), *Pinus contorta* (Peterson and Arbaugh 1986, Reinhardt and Ryan 1988, Swezy and Agee 1991), and *Picea engelmannii* (Ryan 1998). Several fir species were also studied such as *Abies lasiocarpa* by Peterson (1985) and Ryan and Reinhardt (1988), and *Abies concolor* by Thomas and Agee (1986) and Swezy and Agee (1991). The effect of fire on mortality of deciduous species is less well known;

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although *Populus tremuloides* has been studied (Brown and Debyle 1987), as well as some oaks associated with maples (Huddle and Pallardy 1999) or with pines (Harmon 1984, Regelbrugge and Conard 1993).

Tree mortality has often been modeled as a function of tree size and fire damage to foliage, stem, and roots (Peterson and Arbaugh 1986, Brown and Debyle 1987, Regelbrugge and Conard 1993, Ryan 1998). Among the different injury types that can kill trees, crown injury is the most commonly observed fire effect whereas little is known about the extent to which roots are affected by fires (Ryan 1998). Even though combined damage should be taken into account to increase the accuracy of mortality predictions, the damage to roots was not investigated in the present study. The height or percent crown scorched have been significant predictors of tree mortality for many species and models (Peterson 1985, Ryan and Reinhardt 1988). Indirect representations of bole damage such as bark charring (percent circumference charred, char depth or char height), have also been found to contribute to mortality predictions (Peterson and Arbaugh 1986, 1989, Ryan and Reinhardt 1988).

According to several authors (Brown and Debyle 1987, Finney and Martin 1993, Ryan 1998), tree diameter is linearly correlated to the bark thickness above about 50 cm on the bole. Because resistance to cambium injury increases with the square of the bark thickness, fire injury resistance is expected to increase with the square of stem diameter (Ryan 1998). However, several studies have successfully used diameter as a linear term in their model (Brown and Debyle 1987, Ryan et al. 1988, Finney and Martin 1993, Harrington 1993), while other studies have shown that tree mortality was not correlated to tree diameter for some species, or above a diameter threshold (Ryan 1998). Thus mortality may be independent of diameter for some species, or for small diameter trees (Gutsell and Johnson 1996). Diameter is also correlated to tree height, which is related to crown base height. All these relationships vary with tree species, site, and stand conditions (open versus closed) (Ryan 1998). The greater the tree size, the greater the portion of the crown is high enough to avoid direct scorching by the flame or scorching by hot gases (Ryan et al. 1988).

Few direct relationships between fire behavior characteristics and effects on trees have been developed. Van Wagner (1973) derived a relationship between fire line intensity and height of convective crown scorch on conifers. Tree mortality of conifer species was estimated under burning experiments in the northwestern United States, and nomograms were created relating tree mortality to fire line intensity and to flame length (Reinhardt and Ryan 1988). Ryan and Frandsen (1991) related cambium mortality of Rocky Mountain conifers to fuel loading and consumption variables. Brown and Debyle (1987) developed models for mortality of small trees based on artificial fire line intensity treatments and tree diameter at ground level.

In the eastern Canadian mixed-wood boreal forests (Rowe 1972), the main tree species are balsam fir (*Abies balsamea* [L.] Mill.), white birch (*Betula papyrifera* Marsh.), black spruce (*Picea mariana* [Mill.] B.S.P.), jack pine (*Pinus banksiana* Lamb.), and trembling aspen (*Populus tremuloides* Michx.). However, these species received little attention for fire-caused tree mortality research [except *Populus tremuloides* by Brown and Debyle (1987)] even though they are key species in boreal forest dynamics. Moreover, aspen, jack pine, and black spruce represent valuable species for the forest industry in eastern Canada.

The objectives of this study were threefold: (1) verify the results of Hély et al. (2001) that stand composition influences fire intensity. Indeed, Hély et al. (2001), using two different fire behavior prediction systems, found that deciduous stands experience less intense fire behavior than mixed or conifer stands; (2) compare mortality rates among different species a few months after a fire to test the hypothesis that deciduous species are less fire-resistant than conifer species; (3) determine which morphologic variables and fire damage indicators are important in predicting tree mortality when modeled with logistic regression. Probability of mortality was hypothesized to be negatively correlated with tree size, and positively correlated with fire-injury.

Materials and Methods

Study Area

A wildfire near Val Paradis (49°09'N, 79°26'W, Northwestern Quebec, Canada) spread during two days in June 1997 and covered 12,557 ha of mixed-wood boreal forest. The principal tree species in the burned area were *Populus tremuloides*, *Picea mariana*, and *Pinus banksiana. Abies balsamea* (L.) Mill. and *Betula papyrifera* Marsh. were secondary species. The fire was an intermittent crown fire, and most of the area was burned during the second day. The fire was extinguished on the third day.

Data Collection

Thirty-six permanent plots (0.04 ha each) were set up a few weeks after the fire to assess tree mortality. Plots were selected to represent deciduous (12), mixed (12), or coniferous (12) stands according to the proportion of coniferous and deciduous basal area. These plot types encompassed homogeneous structure and composition characteristics (Appendix 1). Plot locations were chosen to represent a wide range (from 0 to 100%) of mortality. We classified the 36 plot burns as either being low (12), moderate (12), or extreme (12) fire severity (SEV), if stand mortality was less than 25%, between 25 and 75%, or more than 75%, respectively.

In each plot, we labeled all trees with diameter at breast height (DBH) greater than 5 cm. We recorded the following variables: species, DBH in centimeters, total tree height (TOTH), and crown base height (CBH) in meters, status (live or dead from the fire), char height (CH) on the stem at the four orientations in centimeters, orientation of maximum and minimum char heights, and bark thickness (BT) in millimeters. The specific measured ranges of morphological variables are reported in Appendix 2. We sampled at the end of the first growing season following the fire (3 months after the fire occurred), just before the drop of deciduous foliage occurred. We used the crown status to determine if an individual was dead or live. Moreover, a deciduous tree was considered dead if its crown had no green leaves, while a coniferous tree was considered dead if its needles were all gone or brown.

To have a general idea of the variability of the fire behavior, the mean head fire intensity (*I* in kilowatts per meter) was estimated for each stand using the following series of equations. In the first step, the wind speed above the stand canopy [Equation (1)] and on the ground [Equation (2)] were calculated (Cionco 1978, Amiro and Davis 1988) using the airport wind speed ($u_{airport} = 6$ m/s), recorded at 10 m high ($z_{airport}$):

$$\frac{u_h}{u_{airport}} = \frac{\ln((h-d)/z_0)}{\ln((z_{airport}+h-d)/z_0)} \tag{1}$$

and

$$u_z = u_h * e^{(a(\frac{z}{h}-1))} \tag{2}$$

where *u* is the wind speed (in meters per second) at any height, *z*, in the canopy, *h* is the canopy height (mean stand TOTH in meters), $d = 0.7 * h$, $z_0 = 0.13 * h$, and *a* is an attenuation coefficient or the canopy flow index. We used the values found by Amiro (1990) for *a* (3.2, 2.6, and 4.8 for *Populus tremuloides*, *Pinus banksiana*, and *Picea mariana* stands, respectively), and we assumed constant wind speed ($u_z = u_{0.6h}$) from ground surface to 0.6*h* (Alexander 1998).

In the second step, the flame angle *A* in degrees, measured between the flame front or flame plume and the unburned fuel bed, was related to the wind speed on the ground (Alexander 1998):

$$\tan A = (0.82 * (9.8 h_f / u^2)^{0.5}) \tag{3}$$

where h_f is the flame height in meters, and *u* is the aboveground wind speed (i.e., u_z) in meters per second. Because none of the studied species have shaggy bark that could propagate the combustion higher than the flame height, such as Eucalyptus species (Burrows 1997), and because the wind was strong enough so the flame was not vertical, a condition that could create char and scorch heights higher than the flame heights (Gould et al. 1997), we assumed that flame height was equivalent to char height. When *A* was extracted from Equation (3), the mean stand fire intensity was calculated using the Alexander (1982) relationships:

$$L = h_f / \sin A \tag{4}$$

and

$$I = 259.833 * L^{2.174} \tag{5}$$

where *L* is the flame length in meters, and *I* is the surface fire intensity. We didn't calculate crown fire intensities as recommended by Alexander (1982) because we found that adding one-half of the canopy height to *L* resulted in unrealistic fire intensities (between 10,000 and 90,000 kW/m) as compared to those usually related to intermittent crown fires (5,000 to 10,000 kW/m). Estimates of stand fire intensities with intermediate calculations from the above five equations are reported in Table 1. However, to analyze species or individual tree mortality, we will use only the maximum char height (MACH) variable as we assume char height is a good indicator of flame height and fire intensity.

Data Analysis

Analyses include only *Pinus banksiana*, *Picea mariana*, and *Populus tremuloides* because the other species were underrepresented ($n = 49$ trees for *Abies balsamea*) or had no survivors (such as *Betula papyrifera*).

Effect of Stand Type and Species Composition on Fire Intensity

Respective roles of stand type and species composition on MACH were analyzed using a two-way ANOVA design on rank scores (Conover and Iman 1981) with the General Linearized Model procedure (SAS Institute Inc. 1989, p. 898–899). We tested both factor effects and their potential interaction using the Type III SS outputs. We looked at the differences in MACH among the three stand types and the three species using the Tukey's Studentized Range (HSD) test.

Heterogeneity Tests for Species Mortality Rates

We performed nonparametric likelihood ratio tests, also called G tests or heterogeneity tests (Scherrer 1984, p. 484–488), to study the differences among species mortality rates.

For all species, each tree was classified into one of six maximum char height (MACH) classes (<100, 100–200, 200–300, 300–400, 400–500, and >500 cm, respectively). The G tests were performed within each MACH class. The G test is based on a Chi-square distribution when the sample size is large. When significant differences were found a multiple comparison test (simultaneous test procedure in Scherrer 1984, p. 488–495) was performed to find out the significantly different species groups.

Characteristic Tree Variables Potential Explaining Fire-Caused Mortality

Wilcoxon-Mann-Whitney tests were performed on the morphological variables (DBH, TOTH, CBH, and mean BT, respectively) for each species. The MACH variable was used as an independent variable with the same six classes as for the G tests to study the species resistance relationships. Results of comparisons were plotted to find out which morphologic variables show significant differences between dead and live trees within several MACH classes. A characteristic variable is a morphological variable that, for a given species, displays several significant differences along the MACH gradient.

Logistic Regression Models for Tree Species Mortality Prediction

Tree mortality data are binary (dead or live trees) and have thus been modeled using logistic regression analysis (Peterson and Ryan 1986, Ryan et al. 1988, Swezy and Agee 1991, Finney and Martin 1993, Harrington 1993, Regelbrugge and Conard 1993, Mutch and Parsons 1998). Logistic equations predict the probability of the occurrence of an event, such as mortality of an individual tree, based on a number of fire variables, fire effects, or tree-

Table 1. Estimated mean stand fire intensity based on canopy height, above canopy (*Uh*) and ground (*Uz*) wind speeds, flame angle (*A*), max. char height (*MACH*), and flame length (*L*).

Stand			Mean stand						
			Height	*Uh*	*Uz*		*MACH*	Flame length	Fire intensity
Type	*SEV*	#	(m)	.... (*m/s*).............		tan*A*	(cm)	(m)	(Kw/m)
D	L	1	13	2.38	0.66	2.14	30	0.34	24
D	L	2	20	2.76	0.40	6.50	105	1.06	297
D	L	3	17	2.61	0.73	2.69	58	0.62	91
D	L	4	14	2.44	0.68	2.45	42	0.45	47
D	M	1	21	2.81	0.78	2.53	59	0.64	97
D	M	2	18	2.66	0.39	6.91	111	1.12	330
D	M	3	17	2.61	0.38	5.13	58	0.60	84
D	M	4	21	2.81	0.78	2.78	72	0.76	143
D	E	1	23	2.90	0.81	6.30	391	3.96	5,163
D	E	4	18	2.66	0.39	13.25	406	4.07	5,497
M	L	1	11	2.25	0.33	6.79	76	0.77	147
M	L	2	13	2.38	0.35	5.43	54	0.55	72
M	L	3	17	2.61	0.38	8.51	161	1.62	742
M	L	4	15	2.50	0.37	5.83	69	0.70	121
M	M	1	15	2.50	0.37	12.57	322	3.23	3,330
M	M	2	17	2.61	0.38	8.75	170	1.71	837
M	M	3	17	2.61	0.38	9.15	186	1.87	1,018
M	M	4	16	2.56	0.37	9.90	209	2.10	1,305
M	E	1	17	2.61	0.38	14.98	499	5.00	8,591
M	E	2	15	2.50	0.37	13.70	383	3.84	4,847
M	E	3	15	2.50	0.37	13.02	346	3.47	3,887
M	E	4	19	2.71	0.40	12.50	375	3.76	4,630
C	L	1	10	2.18	0.32	9.42	138	1.38	526
C	L	2	11	2.25	0.33	7.10	83	0.84	178
C	L	3	10	2.18	0.32	6.76	71	0.72	126
C	L	4	9	2.10	0.31	5.81	49	0.49	56
C	M	1	11	2.25	0.33	11.39	214	2.15	1,372
C	M	2	11	2.25	0.33	12.22	247	2.47	1,861
C	M	3	12	2.32	0.82	4.55	210	2.15	1,378
C	M	4	13	2.38	0.35	14.13	369	3.70	4,473
C	E	1	10	2.18	0.32	17.36	467	4.67	7,423
C	E	3	14	2.44	0.36	16.02	499	5.00	8,601
C	E	4	13	2.38	0.35	16.25	488	4.89	8,200

NOTE: D, M, C, for deciduous, mixed, and coniferous, respectively. L, M, E for low, moderate, and extreme fire severity (*SEV*). Maximum char height is assumed to be equal to flame height.

feature predictors (Finney and Martin 1993). Discriminant analysis could also be an efficient statistical analysis to use with binary dependent variables, but logistic regression models are more appropriate when some of the independent variables are qualitative such as the SEV variable (Press and Wilson 1978), and logistic regression is independent of the assumption of multivariate normality (Daniels et al. 1979). Logistic regression analysis was used to model the probability of postfire tree mortality for each species, as a function of tree size and fire injury. The logistic regression model has the following form:

$$P(m) = \frac{1}{1 + e^{-(b0 + b1x1 + ... + bkxk)}} \quad (6)$$

where *P(m)* is the probability of postfire mortality, $x1$ through xk are independent variables, and $b0$ through bk are model parameters estimated from the data. Variables were considered independent and potential inputs when the Pearson's correlation coefficient between two given variables was less than 0.5. We didn't use the significant probability information because the species sample sizes are very large (more than 300), and numerous variables could then be correlated with a small correlation coefficient. The data set for each species was randomly divided in two parts. The first part, corresponding to 75% of the data set, was used to create the logistic model. The SAS logistic procedure (SAS Institute Inc. 1989, p. 1071–1126) was used to perform the stepwise regression and to obtain the maximum likelihood estimate of the model. A generalized Wald's statistic was performed to test regression coefficients of the model. The model goodness-of-fit was first assessed by the Hosmer and Lemeshow test (SAS Institute Inc. 1989, p. 1126). To further evaluate the performance of the species mortality model, the remaining 25% part of the species data set was used *a posteriori* to validate the model. The comparison between the predicted probabilities and the observed outcomes was performed using the Kappa test (Jensen 1996, p. 248).

First, to find out if species have natural intrinsic sensitivity, we analyzed tree species mortality using only the morphology variables (DBH, TOTH CBH, the CBH/TOTH ratio (CR), and BT [mean (MEBT), minimum (MIBT), or maximum (MABT)]. Then we added the fire characteristic variables such as stand fire severity (SEV) and char height [mean (MECH), minimum (MICH), or maximum (MACH)] to the above morphologic variables. Here, we present only the best models.

Table 2. Results from the two-way ANOVA realized on ranked maximum char height and from the multiple comparison tests on the effects of stand types and species on maximum char height.

		ANOVA results			Multiple comparisons among stand types			Multiple comparisons among species		
Fire severity	Source	*n*	*F*	*p*	Deciduous	Mixed	Coniferous	*Populus tremuloides*	*Pinus banksiana*	*Picea mariana*
					(Mean ± SE)					
Low	Overall model	715	5.28	0.0003	56 ± 9 b	103 ± 12 a	82 ± 5 a	44 ± 8 b	112 ± 13 a	88 ± 5 a
	Stand type		4.98	0.0071						
	Species		6.73	0.0013						
Moderate	Overall model	789	43.49	0.0001	84 ± 14 c	215 ± 11 b	244 ± 8 a	91 ± 12 b	231 ± 13 a	253 ± 7 a
	Stand type		12.54	0.0001						
	Species		22.36	0.0001						
Extreme	Overall model	554	179.23	0.0001	401 ± 11 a	423 ± 7 a	480 ± 6 a	347 ± 7 b	489 ± 8 a	480 ± 5 a
	Stand type		N/A	N/A						
	Species		179.23	0.0001						

NOTE: N/A: not applicable. Maximum char height (mean ± Standard Error) in a row followed by the same letter are not significantly different at α = 0.05 for the Tukey's Studentized Range test.

Results

Stand Composition Influence

For low and moderate fire severities, both stand type and species composition have significant effects on MACH (Table 2), whereas species composition is the only significant factor explaining MACH differences for extreme fire severity. Moreover, where both stand type and species composition are significant, there is no interaction between them. The Tukey tests show that for a stand mortality level less than 75% (low and moderate fire severities), deciduous plots had significantly lower MACH than mixed and coniferous plots, and *Populus tremuloides* burned significantly less intensely to produce similar mortality as compared to *Pinus banksiana* and *Picea mariana* trees.

Species Mortality Rates

Comparisons between species mortality rates (Table 3) show that species have significantly different mortality rates at all levels of MACH. *Populus tremuloides* is the least fire-resistant species because its mortality rates are the highest, with all aspen trees dying when conditions exceed 400 cm in MACH. A differentiation between the two conifer sensitivities is however not possible at this level of the analysis.

Morphological Characteristic Variables

Where differences exist, dead trees have smaller DBH, smaller TOTH, smaller MBT, and higher CBH (Figures 1–3). However, all morphologic variables do not present significant differences between dead and live trees for all species and within all MACH classes. It seems that the higher the char height, the higher the mean value for live trees (DBH, TOTH, and Mean BT for all species). For *Pinus banksiana* and *Populus tremuloides*, the two characteristic variables are DBH and TOTH (Figures 1 and 3, respectively), while all morphological variables are characteristic variables for *Picea mariana* (Figure 2).

Tree Species Mortality Modeling

The logistic regressions performed on morphological and fire variables (using the same ranges as Appendix 2) were the best significant models for each species (Table 4). Char height (MICH, MACH, or MECH) is always entered at the first step of the stepwise procedure, followed by a morphological variable (DBH or TOTH). In both cases, DBH and TOTH increase the expected fire resistance, which decreases mortality (Table 4). Moreover, the concordance between the observed outcomes and the predicted probabilities ranges from 87.2% for *Picea* to 93.5% for *Pinus*. According to the Hosmer and Lemeshow goodness-of-fit tests, all models fit the data well, and the Kappa coefficients are quite high. For *P. tremuloides*, the model increases by 64% the prediction of tree mortality from the random prediction (Table 5). Its overall accuracy of 0.83 corresponds with an 83% concordance between the predicted probabilities and the observed

Table 3. Likelihood ratio tests and multiple comparison results for the species sensitivity (susceptibility to be dead 3 months after the fire has occurred).

					Pmortality and multiple comparisons		
Maximum char height (cm)	N	N. dead trees	Under Ho: prob mortality	χ^2 calculated	*Pinus banksiana*	*Picea mariana*	*Populus tremuloides*
0–100	845	145	0.172	8.190	0.12 b	0.15 b	0.22 a
100–200	261	101	0.387	6.590	0.24 b	0.42 a	0.44 a
200–300	219	118	0.539	24.130	0.39 b	0.46 b	0.81 a
300–400	99	68	0.687	30.051	0.10 c	0.63 b	0.94 a
400–500	54	40	0.741	17.926	0.14 c	0.78 b	1.00 a
> 500	580	531	0.916	8.578	0.93 b	0.90 b	1.00 a

NOTE: χ^2 (2; 0.05) = 5.99, so Ho is rejected for all tests. Specific mortality probabilities with the same letter for a given fire intensity test are not significantly different at α = 0.05.

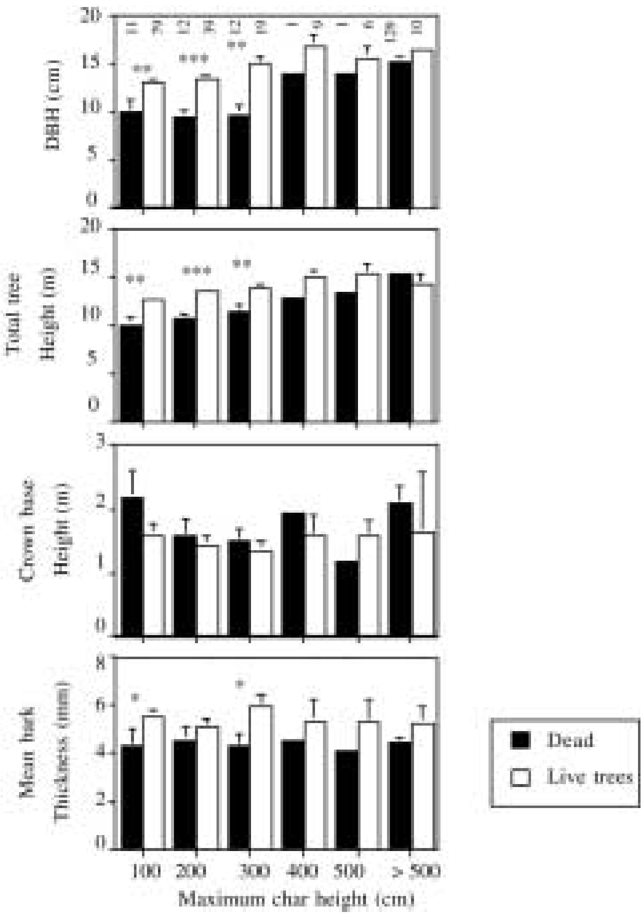

Figure 1. Comparisons in morphological characteristics for dead and live *Pinus banksina* through the maximum char height gradient. Counts per MACH class are presented on the top of the upper graph. Differences result from the Wilcoxon-Mann-Whitney tests (* for $P < 0.05$; ** for $P < 0.01$; * for $P < 0.001$).**

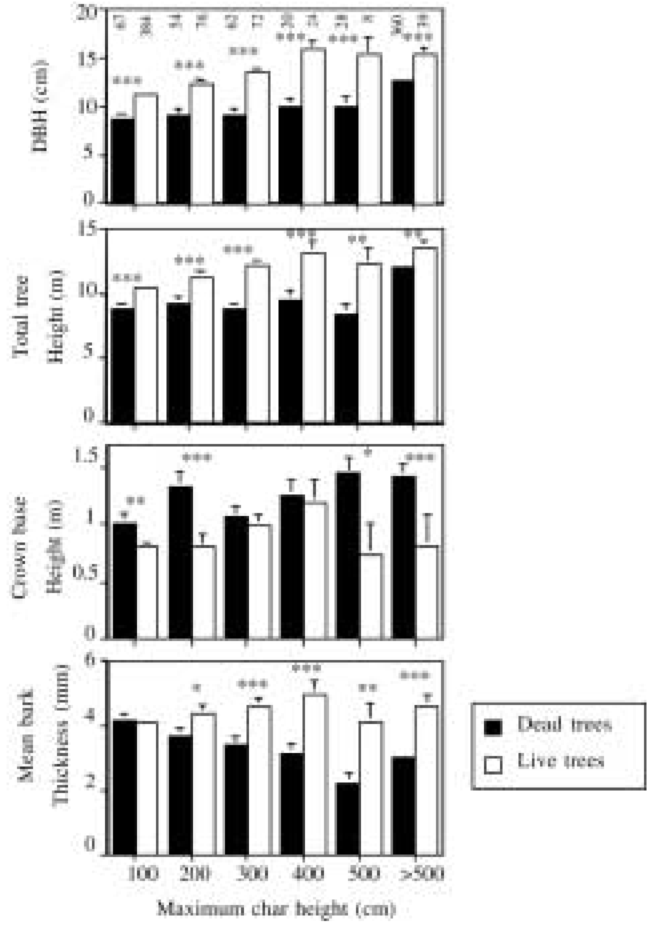

Figure 2. Comparisons in morphological characteristics for dead and live *Picea mariana* through the maximum char height gradient. Counts per MACH class are presented on the top of the upper graph. Differences result from the Wilcoxon-Mann-Whitney tests (* for $P < 0.05$; ** for $P < 0.01$; * for $P < 0.001$).**

outcomes from the validating 25% part. The potential model weakness is explained by the omission and commission errors. The 0.31 omission error for dead trees shows that 31% of dead trees have been predicted alive by the model, while the 0.10 commission error for the dead trees shows that only 10% of living trees have been predicted dead.

Discussion

This study, based on a wildfire, has confirmed the results of Hély et al. (2001) that stand composition influenced fire behavior using char height on tree boles as a fire intensity indicator. This stand composition effect in turn influenced individual tree mortality. At a given level of fire severity (based on the same percentage of stand mortality), tree mortality is greater in deciduous stands than in mixed or coniferous stands. Therefore, this implies that deciduous trees are less fire-resistant than conifers. Fire behavior prediction systems such as the FBP system (Hirsch 1996) simulate significant fire behavior for distinct stand types, but they were not created to look at the species reaction to fire in terms of mortality. The BEHAVE System (Burgan and Rothermel 1984, Andrews 1986, Andrews and Chase 1989) can predict tree mortality, but it takes into account only a few species, mainly from western USA, which cannot be related to boreal species. Moreover, Hély et al. (2001) have shown that the BEHAVE System does not predict fire behavior well in the mixed-wood boreal forest, even using the new fuel model.

Mortality Predictors

This study focused on immediate stem and crown injuries, and several fire-resistance mechanisms confirmed in previous studies (Ryan et al. 1988, Harrington 1993, Regelbrugge and Conard 1993, Mutch and Parsons 1998) have been highlighted for the boreal forest species such as DBH, bark thickness, and total tree height that are negatively related to postfire tree mortality. In trees that survived fire, the values of DBH, TOTH, and bark thickness increased with a rise in char height or fire intensity. Moreover, the two conifer species are good examples of species with interactions between cambium and crown resistances (Regelbrugge and Conard 1993), since DBH, TOTH, and MEBT (particularly for *Picea*) are characteristic variables throughout the fire behavior range.

The greater fire resistance of trees with larger diameter is generally attributed to increased insulation of the cambium by the thicker bark of larger trees (Hare 1965, Ryan and Reinhardt 1988, Peterson and Arbaugh 1989, Mutch and Parsons 1998). Several authors (Harmon 1984, Ryan and Reinhardt 1988) have been criticized by Regelbrugge and

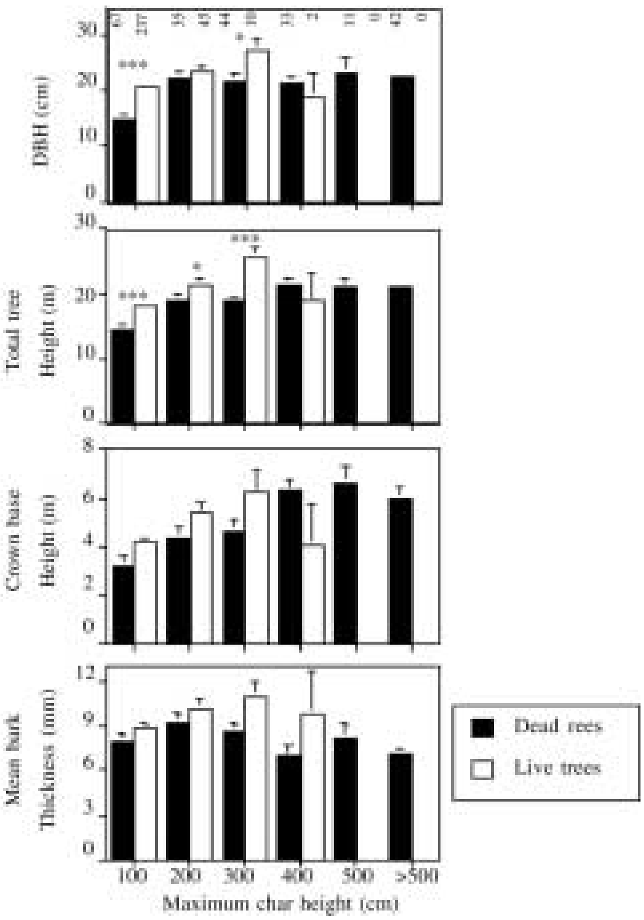

Figure 3. Comparisons in morphological characteristics for dead and live *Populus tremuloides* through the maximum char height gradient. Counts per MACH class are presented on the top of the upper graph. Differences result from the Wilcoxon-Mann-Whitney tests (* for $P < 0.05$; ** for $P < 0.01$; * for $P < 0.001$).**

Conard (1993) for their use of relationships between DBH and bark thickness, when the latter variable was not measured during the field sampling. This study directly measured bark thickness to take into account its natural variability due to site differences, random variability, and age (Regelbrugge and Conard 1993). Gutsell and Johnson (1996) have shown that small-diameter trees will always die because they won't be able to create fire scars as a resistance mechanism. This is because the leeward and windward flames linger for the same amount of time and thus the critical temperature to affect cambial kill is present on all sides of the tree. Conversely, Ryan and Frandsen (1991) have found that some larger trees could die easily when these trees were highly fissured because resistance to fire injury varies somewhat between plates and fissures. This is a possible explanation for *Populus*, which is the thickest bark species in this study, but has the highest mortality rate.

Mortality due to crown scorching has often been related to the total tree height, especially in studies dealing with conifers, with mortality increasing with decreasing tree size (Ryan and Reinhardt 1988). This happens because crowns of smaller trees are closer to the fire and sustain greater injury through crown scorching (Harmon 1984) and also because these small trees are frequently in a low vigor, suppressed state with little tolerance for damage (Harrington 1993). The crown base height of boreal species affects the fire resistance differently than in western conifer species. For *Pinus* and *Populus* species, this variable does not act on fire resistance. For *Picea mariana*, however, it seems to reinforce the cambium resistance (DBH and MEBT), since survivor spruces exhibit CBH no higher than 1 m as compared to dead trees. For this species, the crown base seems to act as a muff and protects the stem from direct flame contact. This result will

Table 4. Logistic regression models for predicting tree mortality using morphological and fire variables.

Species	$Pm = 1/(1+e^{-y})$ where					–2 Log L	Hosmer & Lemeshow goodness (p)	Concordance between predicted probabilities and observed responses (%)	Kappa coefficient
	$y = bo + b1{*}MECH + b2{*}DBH$								
	Variable	b_i	SE	Wald	p				
Pinus banksiana	Constant	3.2362	0.8593	14.1821	0.0002	158.03	0.6777		
$n = 246$	*MECH*	0.0141	0.0017	65.5284	0.0001			93.5	0.52
$R^2 = 0.5209$	*DBH*	–0.4821	0.0835	33.3478	0.0001				
	$y = bo + b1{*}MICH + b2{*}CBH$								
	Variable	b_i	SE	Wald	p				
Picea mariana	Constant	–0.1715	0.2378	0.5201	0.4708	783.68	0.0576		
$n = 914$	*MICH*	0.0133	0.0012	128.1090	0.0001			87.2	0.58
$R^2 = 0.4062$	*DBH*	–0.0859	0.0203	17.9330	0.0001				
	$y = bo + b1{*}MACH + b2{*}TOTH$								
	Variable	b_i	SE	Wald	p				
Populus tremuloides	Constant	0.4501	0.4415	1.0393	0.3080	320.63	0.6585		
$n = 389$	*MACH*	0.0177	0.0020	81.6326	0.0001			87.9	0.64
$R^2 = 0.4258$	*TOTH*	–0.1511	0.0278	29.4847	0.0001				

NOTE *MACH* = Maximum char height (in centimeters); *MECH* = Mean char height (in centimeters); *MICH* = Minimum char height (in centimeters); *DBH* = Diameter at breast height (in centimeters); *TOTH* = Total tree height (in meters).

Table 5. Overall accuracy, omission, and commission errors and Kappa coefficient for each specific logistic regression model.

Species	Under Ho	Overall accuracy	Omission error		Commission error		Kappa coefficient
			Live trees	Dead trees	Live trees	Dead trees	
Pinus banksiana	0.39	0.79	0.02	0.50	0.25	0.06	0.52
Picea mariana	0.55	0.79	0.12	0.28	0.29	0.12	0.58
Populus tremuloides	0.45	0.83	0.07	0.31	0.21	0.10	0.64

have to be explored fully since this characteristic of low CBH has been associated with a less efficient resistance to fire mortality in previous western studies (Harmon 1984, Ryan and Reinhardt 1988). However, if we add to this protection the fact that the photosynthetic power is lower in the lower one-third of the crown than in the middle and upper thirds (Brown and Davis 1973, Ryan 1998), trees that can protect their cambium through the presence of low branches near the ground and if the crowns are not completely scorched these trees will be able to recover from this injury by active and efficient photosynthesis on the upper crown part.

Species Comparisons

Eastern boreal species differ considerably in shape and morphology from most of the studied species, mainly localized in the western part of North America. Indeed, *Pinus banksiana* and *Picea mariana* are thin bark conifer species with conical crown shapes and bases near the ground, and *Populus tremuloides* has fissures (Brown and Debyle 1987) where injury is higher (Ryan 1998), even though it is a tall spherical crown shape species with a relatively thick bark. We think that all the presented effects of morphology and injury variables on mortality depend on the geometrical shape of the tree and the fuel flammability of foliage. Indeed, among reviewed species, pine species dominate with a paraboloid or ellipsoid crown shape at the top of the trunk (Peterson 1985, Peterson and Ryan 1986), which allow trees to escape scorching early during the regeneration phase when they are taller than a minimum height. These species with tall crowns are often characterized as thick bark species (Peterson and Ryan 1986, Mutch and Parsons 1998) with efficiently insulated cambium. Moreover, Brown and Davis (1973, p. 50) explained that conifer species are more susceptible to crown scorch than deciduous species because their foliage is more flammable, and if scorched, these conifer trees would die more easily.

Even though boreal species seem to be very susceptible to fire-induced mortality by their morphology (thin bark for conifers and fissured bark for *Populus*), this study has shown that conifers are quite resistant to postfire mortality. We confirmed the Brown and Davis (1973, p. 53) classification by the mortality rate analysis for *Populus tremuloides* as significantly the least resistant species as compared to the two conifer species, but *Picea mariana* seems to be more resistant in this study than expected by Brown and Davis (1973) classification. Low resistance of *Populus tremuloides* may be explained firstly by the poor crown resistance (almost exclusively effective through the TOTH variable), and secondly by fissures in its bark. Even at low or moderate fire intensity, flames can reach a certain height on the trunk where the fissures are more common than near the base where the bark is also thicker. Ryan and Frandsen (1991) have found the same pattern with large *Pinus ponderosa* trees. Even though a few weeks after the fire several *Populus* seemed to still be alive with char height over 300 cm, these individuals were dead when surveyed the following year. This char height threshold would correspond approximately to 2,900 kW/m in fire intensity. However, the death of individuals does not automatically mean the disappearance of the species, since *Populus tremuloides* is known as an efficient resprouter (Greene et al. 1999). Conversely, the two coniferous species have comparable fire resistances with efficient resistance from cambium and crown through DBH and TOTH, more MEBT and CBH also involved for *Picea mariana*. Moreover, for both conifers few trees with MACH exceeding 400 cm were still alive 1 yr after the fire has occurred (2 and 6 for *Picea* and *Pinus*, respectively) (personal unpublished data).

Model Evaluation and Uses

When stands that contain trees with a wide range of fire resistance burn in a variable fire, there is a high probability that some non-fire-resistant trees will escape serious injury due to localized areas of low fire severity. Likewise, some fire-resistant trees will receive serious injury due to localized areas of high fire severity. In such cases, both morphology and fire behavior variables are needed to adequately predict tree response (Ryan 1998). This illustrates why we obtained a better performance for logistic regressions using both tree morphology and fire behavior variables than using only tree morphology variables. Moreover, our logistic regression models have been validated from independent data sets as only a few studies on tree mortality have done before (Regelbrugge and Conard 1993). In general, the sole model performance appreciation came from the same data and directly from the model. The use of the Kappa coefficient analysis, commonly used in different sciences such as geography (Jensen 1996) is perfectly adapted to validate these models with binary dependent variables, and it should be used in future studies. The char height was the only fire variable included in the stepwise procedure, and it has been previously found as a significant estimator for the postfire mortality (Wyant et al. 1986, Regelbrugge and Conard 1993). Moreover, the models also revealed that DBH was a significant predictor of postfire mortality only when fire characteristics were added. We tried to use the square diameter as recommended by Ryan (1998), but it was not retained as the best significant descriptor in this study. Regelbrugge and Conard (1993) working on *Pinus ponderosa* have found that the best prediction model for postfire mortality was based on char height and DBH. These results are similar to those from our study for *Pinus banksiana*. Char height, found in previous studies to be a poor estimator of absolute flame length or fire intensity was, however, reported as a useful estimator for relative differences in flame length and fire intensity (Cain 1984).

This ecological study, based only on one wildfire, shows that the high natural variability that exists within a fire (broad fire intensity and flame length ranges) and within the morphological characteristics of each species can be taken into account. Authors should particularly pay attention to the relationship they use to relate flame and char heights. Indeed, the relationship between flame and char heights depends on the wind speed, the slope of the terrain, and/or the presence of species with shaggy bark As soon as the wind speed is more than 2 m/s (7.2 km/h), the flame is inclined and it spreads fast enough, producing similar char heights and flame heights on flat terrain (Gould et al. 1997). This was the case in our study with 9 and 20 km/h for the first and the second day, respectively, which justifies our assumption on the equivalence between char and flame heights. However, under no or light wind conditions (less than 7km/h), the flame is vertical and spreads very slowly, which in turn creates char heights to be higher than flame heights as the result of prolongated heated bark and leaves (Gould et al. 1997). For example, this was the case in the study dealing with fire damage, mortality, and suckering in aspen (Brown and Debyle 1987), where two of the three fires analyzed spread with wind speeds less than 7km/h which then produced on average char heights twice as high as the flame heights. Moreover, in that study, analyzed stands were located on a slope, which can also act on the flame-char height.

In order to create useful tools such as nomograms for land managers, based on fire behavior and fire resistance species, other wild or prescribed fire data from the mixed-wood boreal forest should be analyzed and added to this first set to improve the logistic regression models. Nomograms could be useful in evaluating the natural postfire tree mortality, by measuring the mean stand DBH or tree height and maximum char height on stems, in the perspective of wood salvage guidelines. These nomograms could also be used with prescribed burns for a regeneration perspective, such as the ones Brown and Debyle (1987) suggested for *Populus tremuloides* stands through suckering stimulation, or to achieve the desired number and species proportions after fire treatment (Reinhardt and Ryan 1988). In the sustainable management of the mixed-wood boreal forests (Bergeron and Harvey 1997), managers could use these nomograms to rejuvenate some stands (e.g., a mixed-conifer stand toward a mixed-deciduous stand). Results from this study could also improve to a certain extent some existing mortality prediction systems (Andrews and Chase 1989) by the addition of new species.

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APPENDIX 1. Prefire basal area and species tree density Mean and Standard Deviation for the 36 sampled plots burned in the Val Paradis fire.

		Basal area (m^2/ha)		Density (stems/ha)	
Stand type	Species	Mean	SD	Mean	SD
Deciduous	*Abies balsamea*	0.33	0.33	42	42
	Betula papyrifera	2.48	2.46	181	179
	Pinus banksiana	0.23	0.20	8	6
	Picea glauca	0.06	0.06	2	2
	P. mariana	2.53	1.09	188	75
	Populus tremuloides	27.83	3.16	705	99
	Total coniferous	**3.15**	**N/A***	**240**	**N/A**
	Total deciduous	**30.31**	**N/A**	**886**	**N/A**
	Stand total	**33.46**	**3.08**	**1,126**	**137**
Mixed	*Abies balsamea*	0.67	0.37	58	15
	Betula papyrifera	0.05	0.05	8	0
	Pinus banksiana	2.55	1.57	56	44
	Picea glauca	0.00	0.00	0	0
	P. mariana	13.72	2.07	585	81
	Populus tremuloides	19.21	2.49	458	84
	Total coniferous	**16.94**	**N/A**	**699**	**N/A**
	Total deciduous	**19.26**	**N/A**	**466**	**N/A**
	Stand total	**36.20**	**2.51**	**1,167**	**121**
Coniferous	*Abies balsamea*	0.00	0.00	0	0
	Betula papyrifera	0.00	0.00	0	0
	Pinus banksiana	8.89	1.97	623	137
	Picea glauca	0.00	0.00	0	0
	P. mariana	20.00	2.45	2,021	294
	Populus tremuloides	0.02	0.02	2	2
	Total coniferous	**28.90**	**N/A**	**2,644**	**N/A**
	Total deciduous	**0.02**	**N/A**	**2**	**N/A**
	Stand total	**28.92**	**1.73**	**2,646**	**276**

* N/A = not applicable.

APPENDIX 2. Specific ranges for the morphological variables measured on sampled trees (dead and alive).

	DBH (cm)			*TOTH* (m)			*CBH* (m)			*BT* (mm)		
Species	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Pinus banksiana	6	42	14	5	23	14	0	11.7	3	0	14	5
Picea mariana	5	38	12	2	22	11	0	10.2	1.5	0	15	4
Populus tremuloides	5	48	21	2	38	19	0.3	14.8	4.6	1	26	9