NRC Research Press

ARTICLE

Fire spread probabilities for experimental beds composed of mixedwood boreal forest fuels

M.B. Dickinson, E.A. Johnson, and R. Artiaga

Abstract: Although fuel characteristics are assumed to have an important impact on fire regimes through their effects on extinction dynamics, limited capabilities exist for predicting whether a fire will spread in mixedwood boreal forest surface fuels. To improve predictive capabilities, we conducted 347 no-wind, laboratory test burns in surface fuels collected from the mixedwood boreal forest of Saskatchewan. The beds were composed of single fuel types of contrasting characteristics, including feather moss, aspen leaf litter, aspen and alder leaf litter, and twigs. Shredded wood (i.e., excelsior) was included for comparison. An extinction index and logistic model from the literature that balances heat sources and sinks performed well for excelsior, a fuel used to develop the model, but poorly for forest fuels. As a result, we used logistic regression to develop a model for forest fuels finding that fire spread was largely determined by the heat sink, heat of combustion, and fuel bed depth. We found close correspondence between our model and fire spread in an independent sample of beds composed of mixtures of mixedwood fuels ($N = 59$). Our model can serve as a means of analyzing the relative importance of fuels and weather on extinction dynamics during mixedwood boreal forest fires.

Résumé : Alors qu'on assume que les caractéristiques des combustibles ont un impact important sur les régimes des feux via leurs effets sur la dynamique d'extinction, nos capacités à prédire si un feu se propagera dans les combustibles de surface de la forêt boréale mixte sont limitées. Dans le but d'améliorer nos capacités de prédiction, nous avons effectué 347 essais de brûlage en laboratoire, en l'absence de vent, avec des combustibles de surface collectés dans la forêt boréale mixte de la Saskatchewan. Des combustibles ayant différentes caractéristiques, incluant de la mousse hypnacée, de la litière de feuilles de peuplier faux-tremble, de la litière de feuilles d'aulne et de peuplier faux-tremble ainsi que des rameaux, ont été testés individuellement. Du bois déchiqueté (c.-à-d. de la fibre de bois) a été inclus pour fin de comparaison. Un indice d'extinction et un modèle logistique tiré de la littérature qui équilibre les sources et les puits de chaleur avait une bonne performance avec la fibre de bois, un combustible utilisé pour élaborer le modèle, mais ne convenait pas pour les combustibles forestiers. Par conséquent, nous avons utilisé la régression logistique pour élaborer un modèle propre aux combustibles forestiers qui nous a permis de constater que la propagation du feu était en grande partie déterminée par le puits de chaleur, la chaleur de combustion et l'épaisseur de la couche de combustible. Nous avons observé une étroite concordance entre notre modèle et la propagation du feu dans un échantillon indépendant de lits composés de mélanges de combustibles de la forêt mixte ($N = 59$). Notre modèle peut servir de moyen pour analyser l'importance relative des combustibles et des conditions météorologiques sur la dynamique d'extinction lors des feux dans la forêt boréale mixte. [Traduit par la Rédaction]

Introduction

The roles of fuels and weather in determining when, where, and how far fires spread has been debated for the mixedwood boreal forest (e.g., Cumming 2001; Johnson et al. 2001; Larsen 1997) and other ecosystems (e.g., Minnich 2001; Moritz et al. 2004). Clearly, differences in fuels among major mixedwood boreal forest types are important in determining rates of spread and fireline intensity (kW·m^{-1}) under a wide range of weather conditions (e.g., Forestry Canada Fire Danger Group 1992). A difficulty arises, however, in reconciling the effects of fuel variability with the observation that the largest fires in the mixedwood boreal forest, those that account for the vast majority of area burned (Weir et al. 2000), spread across landscapes in large part irrespective of substantial variability in fuel conditions. Along with ignition, surface fire extinction processes are a fundamental determinant of when and where fires spread. Fuels in aspen (*Populus tremuloides* Michx.) forests are widely thought to cause surface-fire extinction more readily than conifer fuels (e.g., Fechner and Barrows 1976; DeByle et al. 1987), although the basis for this conclusion is largely anecdotal. Mixed evidence for the role of aspen in reducing area burned has emerged from field studies (e.g., compare Larsen (1997) and Cumming (2001)). Regardless, aspen's reputation has been the foundation of policy documents calling for the use of forest management to increase aspen dominance and, thereby, reduce area burned across the mixedwood boreal forest (e.g., Tymstra et al. 1998).

It would be useful to compare fuel beds that vary in their propensity to carry a fire under a range of weather conditions as a means of better understanding the processes involved in determining when and how variability in fuels, particularly surface fuels, matters in determining fire size. However, models that might be used for the purpose are either not validated or otherwise unsuited for mixedwood boreal forest fuels. For instance, the extinction index introduced by Wilson (1985) was parameterized for stacked, milled wood and excelsior, though he applied the model to forest fuels that may be expected to differ in important ways. Given substantially higher fuel bed porosity (see discussion of combustion rate regimes and porosity in Nelson 2003), fire extinction dynamics in grass (e.g., Leonard 2009) and shrub systems (e.g., Zhou et al. 2005, Plucinski et al. 2010) may be controlled

Received 10 July 2012. Accepted 3 February 2013.

M.B. Dickinson. Forestry Sciences Laboratory, US Forest Service, Northern Research Station, 359 Main Road, Delaware, OH 43015-8640, USA.
E.A. Johnson. Department of Biological Sciences and Biogeoscience Institute, University of Calgary, Calgary, AB T2N 1N4, Canada.
R. Artiaga. Escola Politecnica Superior, Universidade da Coruña, Avenida Mendizábal s/n 15403 Ferrol, Spain.
Corresponding author: M.B. Dickinson (e-mail: mbdickinson@fs.fed.us).

Table 1. Replication across stands types in which surface fuels were collected along with the number of burns conducted in beds composed of single fuel types. Spruce and jack pine needles were included only in beds composed of mixtures of fuel types.

			Bed type (*N*)			
Stand type	Stands (*N*)	Burns (*N*)	Moss	Aspen litter	Aspen and alder litter	Twigs
Conifer with moss	9	127	83	—	—	44
Aspen	7	124	—	74	—	50
Aspen with alder understory	3	82	—	—	51	31
Open jack pine	4	14	—	—	—	14

by very different processes than those for fires in surface fuel layers (e.g., Zhou et al. 2005; Tachajapong et al. 2009). Indices for predicting fire spread probabilities for boreal forest fuels have been developed for broad forest types (Beverly and Wotton 2007) but these cannot be used to examine the effects of quantitative variability in fuels such as would be obtained by standard fuel sampling in the field (e.g., Bessie and Johnson 1995).

In this paper, we describe fire spread probabilities for laboratory test burns conducted under no-wind conditions in beds composed of different types of mixedwood boreal forest surface fuels and compare our results with predictions from Wilson's (1985) logistic model and associated extinction index. Here, fire spread most closely corresponds to "sustainability" in Anderson's (1970) concept of fuel bed flammability. After testing Wilson's predictions, we found it necessary to parameterize a separate model with our data from fuel beds composed of single fuel types. We evaluate the model by comparison with an independent sample of burns in beds composed of mixtures of fuel types.

Methods

Phenomenological model

Ignition is followed by either extinction or flame spread in open combustion systems. The alternative states are determined by the ratio of heat gained by the unburned fuel from in-bed combustion and the overbed flame and heat requirements for gasifying the fuel (e.g., Emmons 1964; Frandsen 1973). Extinction and flame spread are separated by an unstable state from which small excursions in heat-flux feedbacks determine whether the fire spreads or goes out, a situation that is one of a class of bifurcation phenomena (Williams 1982). In lieu of a more process-based approach, and in keeping with the bifurcated nature of the process, we use logistic regression and a group of key variables (the index) to describe extinction.

Wilson (1985) proposed an extinction index that was intended, in an integrated way, to describe the ratio of a fuel bed's potential heat source (numerator, kJ·kg^{-1}) to its heat sink (denominator, kJ·kg^{-1}) and used that index in a statistical model (the logistic) to predict the characteristics of fires near their extinction limit. The variables in Wilson's extinction index are as follows:

$$[1] \qquad \frac{\text{Heat source}}{\text{Heat sink}} = \frac{hS}{Q_T}$$

where h is the heat of combustion (kJ·kg^{-1}, either total or volatiles alone), Q_T (kJ·kg^{-1}) is the total energy required to carry the fuel through pyrolysis (see below), and S is the surface area of fuel per unit area of the fuel bed (dimensionless). The fuel bed surface area is defined as

$$[2] \qquad S = \sigma\beta\delta$$

where σ is the fuel particle surface-area-to-volume ratio (m^{-1}), β is the packing ratio (dimensionless), and δ is fuel bed depth (m). The packing ratio is the fraction of the fuel bed volume occupied by solid fuel. The heat source term characterizes the potential heat output from the fuel bed and, through the fuel bed surface area, how effectively the fuel bed absorbs energy from combustion and the extent to which the fuel particles impede ventilation of the combustion zone (Nelson 2003). Wilson's index itself is re-scaled from eq. 1:

$$[3] \qquad N_{XW} = \frac{\ln\left(\frac{h}{Q_W}S\right)}{\frac{Q_T}{Q_W} + M}$$

where N_{XW} refers to Wilson's extinction index, Q_W (kJ·kg^{-1}) is the fraction of Q_T required to raise the temperature of water in the fuel and cause its vaporization, and M is the ratio of the mass of water in the fuel (wet mass of fuel less dry mass) to fuel dry mass.

Fuel beds

Surface fuels for burn trials were collected from 1 × 1 m plots in the spring of 2001 in 23 mixedwood boreal forest stands (Table 1) in and around Prince Albert National Park, Saskatchewan (from 53°35′N to 54°20′N and from 106°0′W to 106°47′W). Live shrubs were avoided. Spring was chosen because it is the primary wildfire season (Wright and Beall 1934; Johnson et al. 1999). Stands sampled were representative of those described in Bridge and Johnson (2000) and Chipman and Johnson (2002) and were chosen opportunistically. Included were the following: stands on glacial till with an overstory dominated by aspen and fuel beds dominated by either aspen litter or a mixture of aspen and alder litter (*Alnus crispus*); stands on glacial till dominated by white spruce (*Picea glauca*) with forest floor fuels dominated by feather moss; stands on glaciofluvial material with an overstory dominated by either jack pine (*Pinus banksiana*) or black spruce (*Picea mariana*) with fuel beds dominated by feather moss; and open jack pine stands with a substantial loading of needle litter and low shrubs. Moss cover included *Hylocomium splendens, Pleurozium schreberi,* and *Ptilium crista-castrensis* in undefined mixture. These mosses form dense mats up to ~10 cm thick. Replication within stand types is given in Table 1.

Two types of fuel beds were constructed, those of single fuel types and those of mixtures of fuel types. Single fuel type beds were composed of the following: litter from aspen stands; litter from aspen stands with an alder understory; moss; jack pine needles; white spruce needles; and twigs and small branches. Moss was largely live when collected, but dead upon burning after having been dried. Beds composed of spruce needles alone would not carry a fire, presumably because of dense packing and weathering in moss beds in the field. Jack pine needles also packed densely and would not carry a fire at relatively low loadings similar to those that would support flame spread in other fuel types. Because of the lack of spread in initial tests and a need to conserve jack pine fuels for mixed beds, needles were used only in mixed beds. Replication within mixedwood fuel types for single fuel type beds is provided in Table 1. Excelsior beds ($N = 29$), burned in single fuel type beds only, were composed of shredded aspen wood (no bark) from a single bale manufactured by Western Excelsior of Mancos, Colorado, USA.

Mixed beds were composed of aspen leaf litter and twigs ($N = 26$ beds); moss, needles, and twigs ($N = 29$); and moss, needles, twigs, and aspen leaf litter ($N = 4$). Proportions of each fuel type across all beds are given in Table 2. Litter from aspen stands with alder understories and white spruce needles were the least represented fuel types in mixed beds. Twig and branch diameters ranged from 0.8 to 10 mm and were separated into 1 h (<6 mm) and 10 h (≥6 mm) fuel drying classes to facilitate creation of fuel beds with a wide range of characteristics. Except for dead twigs and small branches from two spruce stands that were collected from live trees and burned as single fuel class burns ($N = 15$), all twigs and small branches used in fires were collected from the litter layer.

Replicate estimates of fuel particle surface-area-to-volume ratios (σ, m^{-1}) were based on measurements of about 20 particles. Needles and twigs were assumed to be cylinders and their σ values were estimated from diameter measurements and eq. 4 in Brown (1970). Excelsior particle cross-sectional area approximated a rectangle, and width and diameter measurements were used to estimate σ values. For needles, twigs, and excelsior, the contribution to surface area of particle ends was ignored for purposes of calculations. Surface area-to-volume ratios were estimated on all excelsior fuel beds and all twig beds burned as single fuel class beds (each was composed of one size class), and these values were used directly in analyses. Surface-area-to-volume ratios of leaf litter from aspen and aspen and alder foliage were estimated by assuming that the perimeter of particles added little to surface area. Accordingly, σ for broadleaves in Brown's (1970) eq. 5 simplifies to $2/d$, where d is leaf thickness. Surface-area-to-volume ratios of leaf litter from aspen and aspen and alder stands were measured on a subset of beds, and the resulting means were used in all analyses. Because of the difficulty in defining and characterizing moss surface area, we assigned a value of 25 000 m^{-1} (Sylvester and Wein 1981). For mixed beds, each fuel type was assigned the average σ of all beds of that fuel type that were burned as single fuel class beds (there being two size classes for twigs as described above).

Fuel beds were manipulated in their moisture content, loading, and bulk density. Both single and mixed beds were assembled in paper bags, dried at 50 °C until weight loss ceased, and then weighed to determine dry mass. The relatively low drying temperature was used to minimize loss of volatile waxes and oils. Fuel beds were either burned soon after drying, burned some hours or days after drying, or wetted to various degrees before burning. To wet fuels, water was applied thoroughly as a fine mist with a spray bottle until somewhat more than the desired moisture content was achieved. The beds were then allowed to sit until liquid water on the surface of the particles was either absorbed or evaporated. Woody fuel beds were allowed to sit in plastic bags for several hours or, for larger diameter particles, overnight to increase moisture absorption. Fuel beds were re-weighed to obtain final wet masses just prior to burning.

Bulk density was manipulated by varying packing (i.e., depth for a given loading) over as large a range as possible under the constraints that particles were not artificially reduced in size or that beds were not assembled one particle at a time either in self-supporting arrays to achieve the lowest packing possible or in some repeated orientation to maximize packing. To increase packing, beds were either compressed by hand or shaken so that particles packed more closely. To reduce packing, moss, twig, and excelsior beds were teased by hand. Nelson (2003) uses dimensionless porosity (porosity divided by fuel bed depth) to classify fuel beds. Beds in which combustion rates are expected to be limited by ventilation have a dimensionless porosity of about 1, whereas those expected to be limited by the availability of fuel surface area have dimensionless porosities greater than 1. We characterized our fuel beds based on Nelson's criterion.

Table 2. Proportions of total fuel bed mass of different fuel types used in beds composed of mixtures of fuel types. The number of mixed-fuel beds in which a given fuel type was used is also shown.

		Proportion	
Fuel type	Burns (N)	Minimum	Maximum
Moss	33	0.15	0.63
Aspen litter	27	0.46	0.91
Aspen and alder litter	3	0.91	0.91
Twigs	59	0.04	0.54
Jack pine needles	30	0.23	0.58
White spruce needles	4	0.30	0.31

For beds composed of mixtures of fuel types, the weighted-averaging technique introduced by Rothermel (1972) was used to estimate for each bed a single value of the thermochemical variables (see below), fuel particle surface-area-to-volume ratio, and fuel moisture. The weighting of each fuel type is a dimensionless function of surface-area-to-volume ratio, fuel mass, and (constant) particle density. Particle densities were set to a constant 512 $kg \cdot m^{-3}$ (Rothermel 1972) because of a lack of further information.

Fuel thermochemistry

Testing Wilson's (1985) model requires information on fuel thermochemistry. Total and char heats of combustion were determined from oxygen bomb calorimetry, and other variables were either measured or estimated by difference. Total heat of combustion is partitioned as follows (Albini 1979):

$$h_T(1 - \psi) = h_V(1 - \gamma) + h_C(\gamma - \psi) \tag{4}$$

where h_T is the heat of combustion of char and volatiles combined ($kJ \cdot kg^{-1}$), h_V is heat of combustion of volatiles ($kJ \cdot kg^{-1}$), h_C is char heat of combustion ($kJ \cdot kg^{-1}$), and ψ and γ are ash and char fractions, respectively. Total heats of combustion were determined on ground, air-dried samples. The mass remaining after combustion was used to estimate ash fraction. Char content was evaluated by heating samples of about 8 mg of fuel in a thermobalance with inert atmosphere (argon purge at 50 $mL \cdot min^{-1}$) at 10 $°C \cdot min^{-1}$ from ambient to 505 °C at which temperature they remained for 5 min to ensure full conversion to char. Susott's (1982) heating rate was 20 $°C \cdot min^{-1}$, but his results suggested that we should expect little difference between heating rates. To obtain larger amounts of char for evaluating heats of combustion, larger amounts of fuel were placed in glass tubes with argon purge and were kept in an electrical furnace at the same temperature (505 °C) for 5 min. Heat of combustion of volatiles was estimated from eq. 3. Thermochemistry for forest fuels was quantified only for materials collected from the forest floor.

Laboratory test burns

Fuel beds 30 cm wide and 40 cm long were heated by propane torch along the edge of one of their short sides until the fuels sustained flaming, and then, whether the fire spread across the length of the plot was noted. The beds were composed of single fuel types (aspen leaf litter, moss, twigs, and excelsior) and mixtures of fuel types (aspen leaf litter and twigs, moss and needles, and combinations of all four) spanning a large range in moisture, loading, and packing ratio. The base of the bed was ceramic fiber board resistant to temperatures <3000 °F and manufactured by Cotronics Corporation (www.cotronics.com).

Baffles were positioned along the long sides of each plot (i.e., in the direction of fire spread). The baffles were 25 cm high and 40 cm long and were constructed of aluminum flashing material

Table 3. Thermochemistry of fuels burned in this study.

Material	Char (%)	Ash (%)	h_C (kJ·kg⁻¹)	h_T (kJ·kg⁻¹)	h_V (kJ·kg⁻¹)
Leaf litter					
Aspen overstory	37 (6, 1.1)	11.4 (6, 1.0)	24 309 (2, 1449)	16 946 (6, 291)	16 974 (2, 534)
Aspen and alder	37 (3, 1.1)	12.1 (3, 1.8)	28 116 (1, NA)	16 203 (3, 249)	14 472 (1, NA)
Needles					
Spruce	35 (4, 2.2)	10.4 (6, 2.5)	22 402 (3, 662)	17 309 (6, 1122)	16 298 (1, NA)
Open jack pine	31 (4, 1.4)	5.9 (4, 2.0)	26 642 (3, 1003)	18 647 (4, 394)	17 184 (3, 223)
Moss					
Jack pine and black spruce	37 (6, 2.3)	9.0 (6, 3.4)	25 763 (6, 2240)	15 114 (5, 564)	12 421 (5, 1389)
Twigs					
Jack pine and black spruce	33 (6, 2.9)	5.0 (6, 1.8)	27 184 (3, 2904)	18 326 (6, 701)	15 669 (3, 911)
Aspen	31 (6, 1.6)	7.0 (6, 1.6)	25 142 (2, 781)	17 793 (6, 411)	17 191 (2, 368)
Aspen and alder	29 (3, 1.0)	5.7 (3, 1.6)	—	17 263 (3, 299)	—
Open jack pine	31 (4, 2.3)	5.1 (4, 1.7)	27 977 (2, 373)	18 087 (4, 541)	15 496 (2, 339)
Excelsior					
Aspen wood	29 (3, 3.1)	4.1 (3, 1.6)	—	18 233 (3, 994)	—

Note: The sample size (number of stands, see Table 1) and standard deviation are shown in parentheses. Heat of combustion of char (h_C) and total (h_T) and volatile (h_V) heats of combustion are given (see eq. 4). Data for white and black spruce needles separated from moss beds are combined. NA indicates a lack of replication.

supported by a wooden frame. The baffles were intended to prevent inflow of air along the margins of the burn so that the combustion, where it proceeded in a roughly linear fashion across the bed, would mimic a longer fire line. The baffles were allowed to blacken from deposition. By observation, flame heights across the width of the fuel bed were remarkably consistent, suggesting that the baffles served their intended purpose.

Statistical analyses

Wilson's (1985) logistic model was used to predict fire spread probabilities for our fires in beds composed of single fuel types. We used Wilson's parameters specific for whether a fire spread across a fuel bed, a descriptor congruent with our categorization of fires. Wilson also provides parameters describing proportion of fire line aflame and probability of burning with a contiguous, steadily spreading flame front. Wilson's model for fire spread probability is as follows:

$$[5] \qquad P_0 = \frac{1}{\left(1 + \exp\left[\dfrac{-\pi(N_{XW} - \bar{k})}{\sqrt{3}s}\right]\right)}$$

where $\bar{k}$ and s are parameters of the logistic distribution whose values are 4 and 1.2, respectively. A fire spread probability of ≥0.5 was assumed to predict spread across the bed, whereas a probability of <0.5 was assumed to correspond to no spread or spread across only part of the bed. Concordance statistics were calculated between Wilson's predictions and our results. All analyses were performed with SAS (SAS Institute Inc. 2008).

Because Wilson's model was limited in the accuracy of its predictions of surface fire spread in our forest fuels (see below), we used logistic regression (PROC LOGISTIC) to develop our own model that best met the multiple objectives that (*i*) the model include all fuel variables, (*ii*) the assumptions of logistic regression were met, (*iii*) the model be as simple as possible, and (*iv*) the model fit to the entire data set of single fuel class beds should be as good as possible. Compromise was required to best meet these objectives simultaneously. The simplest model that we tried involved the use of the dimensionless group of variables in eq. 1. The most complex model (i.e., the one with the most parameters) involved including all of the variables listed in eqs. 1 and 2 separately in the model. The approach was to natural-log transform the group of variables described in eqs. 1 and 2 so that parameters estimated from logistic regression would be analogous to exponents for each independent variable and that homogeneity of variances in independent variables would be maximized. Estimating exponents statistically obscures the physical meaning of the resulting statistical model because the dimensions of the variables become meaningless. No intercept was included in our final logistic models because including one did not improve fit. We evaluated the likely effects that multicollinearity among independent variables would have on logistic regression by examining tolerance and variance inflation statistics calculated from multiple linear regression using the same variables as the logistic regression (Allison 1999).

The heat sink (denominator) was calculated as follows (see Susott (1982) and Wilson (1985) for details):

$$[6] \qquad Q_T = Q_P + Q_W M = Q_P + 4.186(100 - T_F + 540)M$$

where Q_P is a constant heat of pyrolysis (700 kJ·kg⁻¹), Q_W is the heat required to raise the temperature of water in the fuel and carry it through vaporization, T_F is fuel bed temperature (°C), and M is the ratio of the mass of water in the fuel (wet mass of fuel less dry mass) to its dry mass.

We evaluated our final logistic model parameterized with data from single fuel type beds by using it to predict spread in fuel beds composed of mixtures of fuel types. We predicted spread in mixed fuel beds when the predicted probability of spread P_0 was ≥50% and compared those predictions with burn results by χ^2 test and concordance statistics. As described above, Rothermel's (1972) weighted averaging method was used to calculate a fuel bed average for each variable for inclusion in the model.

Results

Fuel particle and bed characteristics

Surface fuel thermochemistry is summarized in Table 3 wherein a replicate refers to a single, unique stand (stand types are noted in Table 1). Ash fractions ranged from 4.1% for excelsior to 12.1% for aspen and alder litter. Char fractions varied less, from between 29% and 37%. Moss, although it has the highest surface-area-to-volume ratio (Table 4), had the lowest total and volatile heats of combustion among fuel types burned in this study. Moss volatile heats of combustion were particularly low because of the combination of a low total heat of combustion, high char fraction, and moderate ash fraction. Fuels from only a subset of stands were included in thermochemistry determinations to reduce costs. Missing values for a given fuel type were estimated by averaging values from stands of the same kind.

The physical characteristics of fuel particles and beds (those composed of both single and mixtures of fuel types) are summa-

Table 4. Fuel bed and particle characteristics for single and mixed fuel type beds.

Variable	Fuel bed	Mean	Minimum	Maximum	SD
h_T (kJ·kg⁻¹)	Moss	16 619	16 499	16 757	90
	Aspen	19 128	18 775	19 375	201
	Aspen and alder	18 420	18 324	18 515	79
	Twigs	18 909	18 291	20 119	426
	Excelsior	18 985	NA	NA	NA
	Mixed	18 082	16 988	19 119	889
h_V (kJ·kg⁻¹)	Moss	7786	6326	8637	773
	Aspen	10 798	10 250	11 223	331
	Aspen and alder	9166	9059	9259	85
	Twigs	11 061	9489	12 038	706
	Excelsior	11 917	NA	NA	NA
	Mixed	9551	8250	10 803	1037
σ (m⁻¹)	Moss	25 000	NA	NA	NA
	Aspen	13 204	NA	NA	NA
	Aspen and alder	14 239	NA	NA	NA
	Twigs	1019	470	2318	389
	Excelsior	10 521	7345	15 162	1537
	Mixed	14 072	1628	22 724	7570
β (dimensionless)	Moss	0.011	0.004	0.040	0.006
	Aspen	0.026	0.018	0.041	0.005
	Aspen and alder	0.036	0.020	0.054	0.007
	Twigs	0.067	0.017	0.143	0.023
	Excelsior	0.014	0.003	0.039	0.009
	Mixed	0.022	0.009	0.041	0.008
δ (m × 10²)	Moss	3.9	0.9	10.7	2.1
	Aspen	3.1	0.5	6.5	1.7
	Aspen and alder	2.6	0.4	4.9	1.4
	Twigs	2.6	0.9	7.9	1.4
	Excelsior	4.0	1.3	10.6	2.4
	Mixed	3.5	1.9	7.3	1.2
M (%)	Moss	24	<0.1	111	19
	Aspen	13	<0.1	56	10
	Aspen and alder	8	0.1	24	7
	Twigs	12	<0.1	88	15
	Excelsior	63	3	195	59
	Mixed	22	3	81	22
Q_T (kJ·kg⁻¹)	Moss	1330	701	3594	493
	Aspen	1042	689	2157	250
	Aspen and alder	899	704	1320	184
	Twigs	1005	701	3004	404
	Excelsior	2347	774	5868	1543
	Mixed	1264	784	2829	575

Note: Replication is the number of burns given in Table 1, except for surface-area-to-volume ratios for aspen and aspen and alder litter, for which an average was applied (see Appendix A, Table A1), and moss, for which a constant was used. Fuel moisture is given for convenience, although it was included in the model as part of the heat sink. h_T, total heat of combustion; h_V, heat of combustion of volatiles; σ, surface-area-to-volume ratio; β, packing ratio; δ, bed depth; M, fuel moisture; Q_T, heat sink; NA indicates a lack of replication.

rized in Table 4. Supplementary fuel particle surface-area-to-volume ratios are provided in Appendix A, Table A1, needed because fuel particle surface-area-to-volume ratios were not measured on all aspen and aspen and alder fuel beds. The range in dimensionless fuel bed porosity (Nelson 2003) was 0.04 to 2 for single fuel type beds (with all but a few twig beds being <1) and from 0.04 to 0.9 for mixed beds. Assuming a threshold of 1 between ventilation and surface-area control regimes, we did not segregate our data set by Nelson's criteria because of a lack of data from high-porosity beds. The data set from this study is available as Supplementary data.[1]

Predicting fire spread probability

Predictions of successful spread from Wilson's (1985) logistic equation were most accurate for excelsior fuels (a 14% misclassification rate) and overpredicted spread for forest fuels (Table 5). Overprediction of burn probabilities ranged from 25% to 66%. Fit was particularly poor for burns in litter from both aspen and aspen and alder stands. As a consequence, we did not evaluate Wilson's model as a predictor of spread in beds composed of mixtures of fuel types. Instead, we used logistic regression to develop our own model from data on burns in single fuel type beds.

We tested logistic regression models that ranged in the degree of grouping of variables to find the model that best met the list of objectives outlined in Methods. In general, the fit improved as more variables were entered into the model independently rather than as part of a group of variables, that is, as more parameters were estimated. When all variables in eqs. 1 and 2 were entered independently, however, multicollinearity was unacceptably high, as indicated by tolerance values <0.4 for surface-area-to-volume and packing ratio in linear multiple-regression analyses of binary spread data (Allison 1999). To reduce multicollinearity to acceptable levels (i.e., tolerance values approaching 1 for all vari-

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfr-2012-0291.

Table 5. Spread probability predicted from Wilson's (1985) model and its fit to our burns in beds composed of single fuel types.

	Predicted (%)			
Observed	Spread	No spread	χ^2	*P*
Moss				
Spread	13 (15.8)	42 (51.2)	7.6	0.006
No spread	0 (0)	27 (32.9)		
Aspen				
Spread	1 (1.4)	49 (66.2)	0.5	0.5
No spread	0 (0)	24 (32.4)		
Aspen and alder				
Spread	0 (0)	30 (58.8)	NA	NA
No spread	0 (0)	21 (41.2)		
Twigs				
Spread	9 (13.2)	16 (23.5)	14.3	0.0002
No spread	1 (1.5)	42 (61.8)		
Excelsior				
Spread	11 (37.9)	0 (0)	16.5	0.0001
No spread	4 (13.8)	14 (48.3)		

Note: NA indicates an inability to calculate the χ^2 statistic.

ables), we used the product of surface-area-to-volume and packing ratio in the final model:

$$[7] \qquad N_X = \frac{h^j \sigma \beta^k \delta^l}{Q_T^m}$$

where N_X is the extinction index, and *j, k, l,* and *m* are parameters estimated from logistic regression after natural-log transformation of eq. 8:

$$[8] \qquad P_0 = 1/(1 + \exp[-(j \ln(h) + k \ln(\sigma\beta) + l \ln(\delta) + m \ln(Q_T))])$$

Combining surface-area-to-volume and packing ratios resulted in little effect on parameter estimates for the other variables relative to the model in which all variables were included independently.

Fit between eq. 8 and spread behavior in beds composed of individual fuel types is illustrated in Fig. 1. The model, parameterized with data from all fuel types combined, exhibited a high propensity to assign higher spread probabilities to fires that spread than to nonspreading fires, as indicated by the large area under the receiver operating characteristic (ROC) curve (Table 6). It made little difference to the fit whether total or volatile heat of combustion was used. Heat source variables had positive effects on spread probability, whereas the sink variable had a negative effect on spread probability (Table 6). Fuel bed depth and heat of combustion had much larger effects on spread probability than the product of fuel particle surface-area-to-volume ratio and fuel bed packing ratio as indicated by Wald χ^2 values.

Excelsior beds were not included in the final model (whose parameters are given in Table 6) because excelsior had a greater propensity to carry a fire than mixedwood boreal forest fuels, given the variables that we included in the models that we tested (which were also the variables used by Wilson 1985). Underprediction of spread probability in excelsior beds by the model parameterized with data from mixedwood boreal fuels alone (Table 6) is illustrated in Fig. 2. When the model based on forest fuels was used to predict spread in excelsior by classifying as successful fires in all beds for which predicted probabilities were ≥50%, spread in excelsior was underpredicted by 38%, that is, gave false negatives for 11 of 29 burns.

Evaluating fire spread probability predictions

The fire spread probability model (eq. 8, with parameters from Table 6) was used to predict spread (predicted probability ≥50%) for mixed fuel beds, and the binary results were compared with data on whether actual fires spread across the bed's entire length (Table 7 and Fig. 3). Correspondence between model and data was significant with no apparent bias towards over- or underprediction. Total misclassification rates were 10% and 7% for total and volatile heats of combustion, respectively.

Discussion

The fire spread probability model (eq. 8), with parameters estimated from a data set of fires in experimentally constructed fuel beds composed of single fuel types collected from the forest floor of mixedwood boreal forest stands (Table 6), adequately captured the probability of spread in beds composed of mixtures of fuel types (Table 7 and Fig. 3). Although the model was based conceptually on Wilson (1985), we developed our own model because Wilson's logistic model was a poor predictor of spread in mixedwood boreal forest fuel beds. The good fit between our model and data on burns in beds composed of realistic mixtures of fuel types provides some confidence that the model has relevance to spread probabilities in real mixedwood boreal forest surface fuels.

In this paper, we focus on spread probabilities that are closest to "sustainability" in an overall concept of flammability described by Anderson (1970) and Martin et al. (1994). Their flammability concept also incorporates propensity to ignite and total and rate of consumption, as extended by Martin et al. (1994). We did not consider ignition in our study because we felt that there would be a need to simulate realistic ignition conditions (e.g., ignition from lightning strikes and smoldering duff during holdover conditions), which are not trivial to reproduce (e.g., Latham and Williams 2001). At the small spatial extent of our experiments, rates of spread and, thus, combustion rate estimates would present scaling issues if for no other reason than the fact that no steady state is reached for the more vigorous fires. Estimating spread probabilities in our small beds may overestimate spread probabilities for fires that barely spread across the bed (and would not have if the bed had been larger). Also, spread probabilities predicted from our model may be too large where wildland fuels are patchy (Miller and Urban 2000).

Apart from Wilson (1985), few studies are comparable with ours in the sense that our study focused on surface fire spread probabilities in relatively compact beds and experimentally manipulated fuel bed characteristics, including fuel moisture. Studies that focus on porous grass and shrub fuels are not easily comparable with our study (see below). Because different aspects of flammability (Anderson 1970; Martin et al. 1994) are sensitive to different fuel characteristics (e.g., Ganteaume et al. 2011; Curt et al. 2011), studies that do not provide data on spread probabilities (e.g., Fonda 2001; Kane et al. 2008) are also not easily compared with ours. Ganteaume et al. (2011) and Curt et al. (2011) measured areal extent of fire spread in small test beds collected from Mediterranean ecosystems in southeastern France. Aerial extent is an independent variable that is similar to our measurement of whether a fire spread completely across a given bed. Ganteaume et al. (2011) found that spread was not significantly related to litter depth, in contrast to our results. However, our range in fuel depths was considerably larger than theirs because we manipulated depth experimentally. Spread in their study was also not related to vegetation type or past fire regime, which had effects on other aspects of flammability. In contrast, Curt et al. (2011), in a study involving other Mediterranean fuel beds, found that deeper fuel beds with higher loadings more readily sustained fire spread. These fuel beds tended to come from sites where time since fire was greatest and for sites with particular vegetation structures. In contrast to our study, both Ganteaume et al. (2011) and Curt et al

Fig. 1. Fit to different fuel types (*a*–*d*) of the spread probability model parameterized from the entire data set of burns in single fuel type beds. Shown are experimental values (symbols) and predicted values (line) for all fuel types. The heats of combustion used were those estimated for volatiles. Parameter values and overall fit of models to data are provided in Table 6.

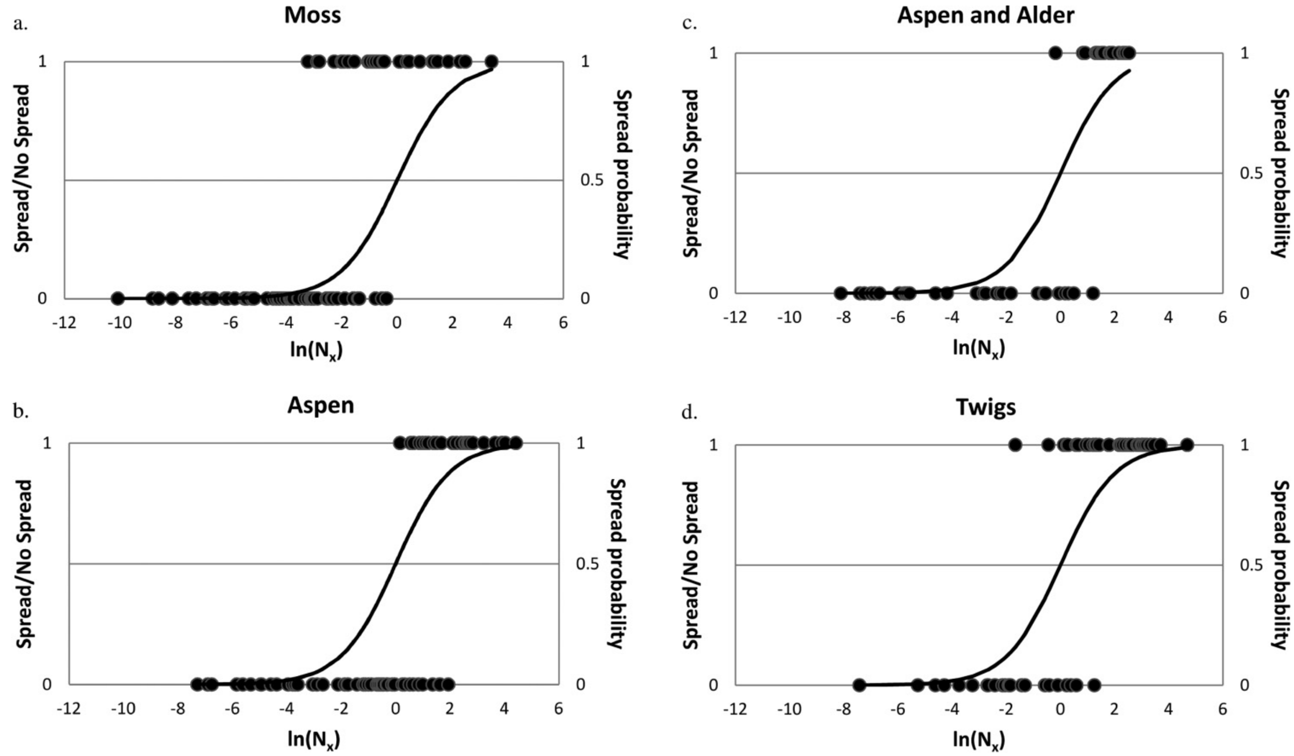
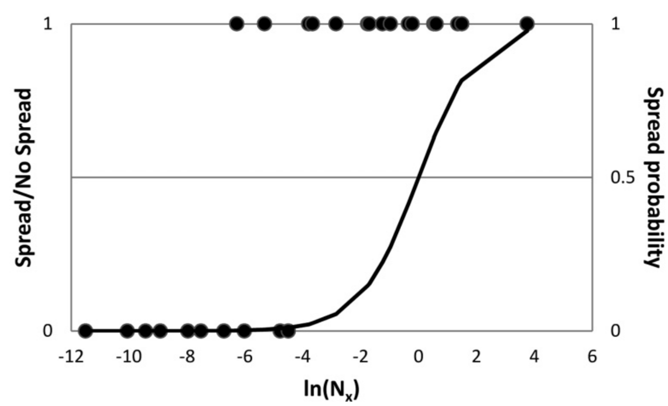


Table 6. Parameters of an extinction index estimated from logistic regression for fuel beds composed of single classes of mixedwood boreal forest fuels (N = 378). Excelsior beds were excluded (see Results). The area under the receiver operating characteristic (ROC) curve (c) is shown. Results for both total and volatile heats of combustion are reported.

Variable	Exponent	Estimate	SE	Wald χ^2	P
Total heat of combustion, logistic regression max-rescaled R^2 = 0.76, c = 0.95					
h_T	j	8.58	1.09	61.9	<0.001
$\sigma\beta$	k	−0.80	0.30	7.7	0.006
δ	l	4.27	0.65	43.6	<0.001
Q_T	m	−9.48	1.24	58.3	<0.001
Heat of combustion of volatiles, logistic regression max-rescaled R^2 = 0.68, c = 0.93					
h_V	j	6.18	0.76	66.4	<0.001
$\sigma\beta$	k	−0.08	0.22	0.1	0.73
δ	l	3.40	0.51	44.3	<0.001
Q_T	m	−6.50	0.84	59.1	<0.001

Fig. 2. Spread predicted in excelsior fuel beds using the logistic model developed from burns in single-class beds composed of boreal mixedwood fuels (see Table 6). Shown are experimental values (symbols) and predicted values (line) for the model that included heat of combustion of volatiles.



(2011) worked with dry fuels to mimic conditions of high fire danger, whereas we also simulated marginal conditions by varying fuel moisture over a large range.

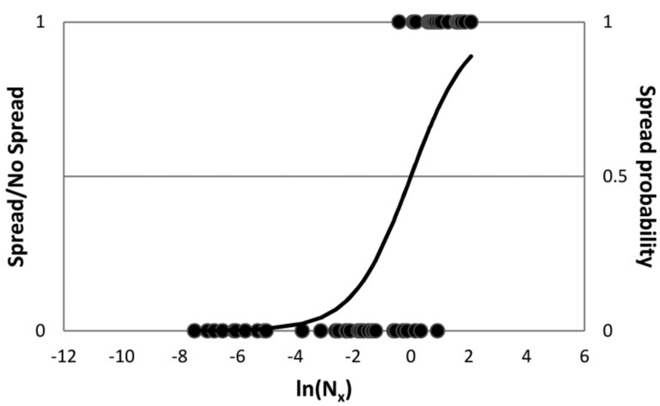
Surface-area-to-volume ratio was less important in describing spread probability than other variables such as heat of combustion and fuel depth (Table 6), despite a range of more than an order of magnitude in its value among beds composed of single fuel types (Table 4). Admittedly, it is unclear at what scale moss surface-area-to-volume ratio (moss being the fuel material with the highest ratio) should be determined because its surface structure varies from individual leaves to the collections of leaves that make up branches and to collections of branches that make up the stem of the gametophyte. Similarly, though we were able to create a range of roughly an order of magnitude in packing ratio, it was not a significant predictor when included as a separate variable in the fire spread probability model.

The limited importance of surface-area-to-volume and packing ratios and the poor fit obtained when the dimensionless surface area variable (eq. 2) was used in logistic regression suggest a limitation in our physical understanding of the relationships between fuel particle and bed characteristics and fire spread. The surface area variable scales with radiation absorption and resistance to air flow for randomly arrayed cylindrical and spherical particles and is sensitive to particle orientation (e.g., Nelson 2003; Vaz et al. 2004). Clearly, more work is needed to characterize energy absorption and ventilation across a range of fuel particle shapes, including the moss and broadleaves used in our experi-

Table 7. Goodness-of-fit between predicted and observed spread for fuel beds composed of a mixture of fuel types (N = 59). Spread (P_0 > 50%) was predicted from eq. 8, with parameter values from Table 6 estimated from beds composed of single fuel types. Predictions based on total (h_T) and volatile (h_V) heats of combustion are shown.

	Predicted (%)			
Observed	Spread	No spread	χ^2	P
h_T				
Spread	33 (55.9)	2 (3.4)	36.7	<0.0001
No spread	4 (6.8)	20 (33.9)		
h_V				
Spread	32 (54.2)	3 (5.1)	44.0	<0.0001
No spread	1 (1.7)	23 (39.0)		

Fig. 3. Spread predicted in beds composed of mixtures of boreal mixedwood fuels. Shown are experimental values (symbols) and predicted values (line) based on the logistic model developed from burns in single fuel type beds (eq. 8 and Table 6). Parameter values are those that correspond to analyses using heats of combustion of volatiles.



ments. Scarff and Westoby (2006) illustrate the application of fluid transfer theory and particle size information to understand ventilation in beds of broadleaves. Increasing leaf size resulted in increased ventilation and combustion rates in their relatively compact beds (see also Kane et al (2008) and Curt et al. (2011)). Rothermel's (1972) method of obtaining average fuel bed characteristics weighs different fuel types by their relative loading and surface-area-to-volume ratios and appeared to work adequately for our mixed fuel class beds. However, a better understanding of how fuel bed structure governs fire propagation should lead to a more physically accurate averaging scheme that provides better fire spread predictions.

Though Wilson's model underpredicted spread probabilities in beds composed of mixedwood boreal forest fuels, the model adequately fit results from our burns in excelsior fuels. Mirroring this difference between excelsior and forest fuels, our model based on single mixedwood boreal fuel types underpredicted spread in excelsior beds (see Fig. 2). One possible explanation for the greater propensity of excelsior to carry fire is that excelsior, being free of bark, has higher rates of moisture and gas exchange upon heating than would be predicted from its surface-area-to-volume ratio, at least relative to twigs and branches. We know of no data comparing wildland fuels with excelsior, but drying rates for masticated woody fuels, with more exposed (bark free) wood surfaces, were the same as for nonmasticated woody fuels (Kreye et al. 2012), a result that does not support our hypothesis. In addition, moisture diffusivities for weathered fuels for which moisture-loss barriers have been compromised are higher than those for recently dead fuels (Anderson 1990) and, perhaps, excelsior. Because we collected fuels during the spring, all of our dead fuels (i.e., all fuels except live moss) had been weathering in the litter bed for greater or lesser amounts of time and would be expected to have higher moisture diffusivities than fresh litter. Instead of diffusivity differences between aspen excelsior and forest fuels, perhaps differences in chemical composition (e.g., terpene concentrations; Owens et al. 1998; Ormeño et al. 2009) account for the differences in spread probabilities. If so, then heats of combustion estimated from bomb calorimetry (e.g., Table 3), although a significant factor in our analyses (Table 6), would not fully account for thermochemical differences among fuels (Owens et al. 1998). Regardless of the mechanism, we conclude that caution should be exercised when using results from excelsior (and, perhaps, milled fuels in general) to predict fire behavior in wildland fuels until we have a better understanding of why fuels differ in their combustion characteristics.

Our results apply only to the fuel types that we included in our experiments and to relatively packed beds of surface fuels in which combustion rates are limited by ventilation (see Nelson 2003). Except for a few twig beds, all beds burned in our study were in Nelson's ventilation-control region. We would not expect our results to apply to spread in fuel beds with low packing ratios such as grass fuels and crown fuels (e.g., Zhou et al. 2005; Tachajapong et al. 2009) where combustion rates are limited by available surface area (Nelson 2003). Further, our models would likely be applicable only to surface fuel beds composed of dead or passively drying material (i.e., moss; Bessie and Johnson 1995) such as those that support the spring fires that account for the most area burned in the mixedwood boreal forest (Johnson et al. 1999). Also, laboratory experiments (e.g., Weise et al. 2005) suggest that our no-wind results would underestimate spread probabilities for fires heading with the wind, though we suspect that fuel bed characteristics would gain in relative importance as winds became more variable in speed and direction. How much winds affect fire spatial patterns on landscapes during marginal burning conditions is an open question.

Where fires start and go out on landscapes and whether fuels play an important role in that process are issues affecting fire and forest management decisions both in the mixedwood boreal forest (e.g., Cumming 2001; Weir et al. 2000) and in other ecosystems (Minnich 2001; Moritz et al. 2004). A surface-fire extinction index sensitive to key fuel characteristics would allow us to further examine the causes of fire spatial patterns and area burned in the mixedwood boreal forest. Understanding the effects of fuel variability will be particularly important in the context of the large fires that, collectively, are responsible for most of the area burned in the mixedwood boreal forest (Strauss et al. 1989). In future work, we intend to use the extinction index, shown here to be a good predictor of spread in beds composed of mixtures of boreal mixedwood fuel types, to explore how mixedwood boreal forest fuel variability determines differences in spread probabilities across a relevant range of weather conditions. In studies from other regions that examined effects of fuel variability on the sustainability of surface fire spread, fire regime (e.g., time since last fire) and species composition of vegetation (e.g., leaf size and shape) have been shown to be important (Ganteaume et al. 2011; Curt et al. 2011). Caution is warranted when extrapolating results from small laboratory fires to the field (Fernandes and Cruz 2012), but we expect that spread probabilities for small-scale experimental fires are good candidates for scaling when burning conditions are marginal.

Conclusions

For a data set resulting from laboratory burn trials in mixedwood boreal forest surface fuels and excelsior, Wilson's (1985) extinction index and logistic model gave adequate predictions for fire spread probabilities in excelsior beds while overpredicting spread probabilities for forest fuels. As a result, we dropped excelsior fuels from our analyses and used logistic regression to develop a fire spread probability model based on fires in beds composed of single fuel types. The resulting model showed good fit to data and provided good predictions of spread probabilities in beds composed of mixtures of mixedwood boreal forest fuel types. Fuel heat of combustion, fuel bed depth, and the heat sink were the most important predictors of spread probability, while fuel particle surface-area-to-volume and packing ratios were least important. We suggest caution in applying models based on data from experimental burns in excelsior and milled wood to wildland fuels. Because values of the variables on which it is based can be estimated from fuel and weather information, our model can be used as a means of analyzing the relative importance of fuels and weather in determining extinction dynamics during mixedwood boreal forest fires.

Acknowledgments

University of Calgary students Claire Solohub, Sang Vo, Eric Johnson, Megan Thompson, Kelly Cunningham, and Becky Ritson-Bennett and Ohio State University students Matt Johnson, Mike Dietrich, and Matt McQueen assisted with fuel sampling and burning trials. Financial and logistical support for this project was provided by Weyerhaeuser Canada, Prince Albert National Park (J. Weir), the Sustainable Forest Management Network of the Natural Science and Engineering Research Council of Canada, the Kananaskis Field Stations (Judy Buchanan-Mappin, Grace LeBel, and Dave Billingham), Department of Biological Sciences of the University of Calgary, and the US Forest Service National Fire Plan. We extend our appreciation to Professor Lisardo Núñez Regueira (deceased) of the Universidade de Santiago de Compostela, who helped make the thermochemical analyses possible. The research was improved by discussions with Bob Essenhigh and Tony Bova, and the manuscript was improved by feedback from Bret Butler, Cynthia Fechner Moser, and anonymous reviewers. Dickinson conducted a large portion of this research while at the University of Calgary, Department of Biological Sciences.

References

Albini, F.A. 1979. Thermochemical properties of flame gases from fine wildland fuels. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, Res. Pap. INT-RP-243.

Allison, P.D. 1999. Logistic regression using the SAS system: theory and application. SAS Institute, Inc., Cary, North Carolina.

Anderson, H.E. 1970. Forest fuel ignitability. Fire Technol. **6**: 312–319, 322. doi:10.1007/BF02588932.

Anderson, H.E. 1990. Moisture diffusivity and response time in fine forest fuels. Can. J. For. Res. **20**: 315–325. doi:10.1139/x90-046.

Bessie, W.C., and Johnson, E.A. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. Ecology, **76**: 747–762. doi:10.2307/1939341.

Beverly, J.L., and Wotton, B.M. 2007. Modelling the probability of sustained flaming: predictive value of fire weather index components compared with observations of site weather and fuel moisture conditions. Int. J. Wildland Fire **16**: 161–173. doi:10.1071/WF06072.

Bridge, S.R.J., and Johnson, E.A. 2000. Geomorphic principles of terrain organization and vegetation gradients. J. Veg. Sci. **11**: 57–70. doi:10.2307/3236776.

Brown, J.K. 1970. Ratios of surface area to volume for common fine fuels. For. Sci. **16**: 101–105.

Chipman, S.J., and Johnson, E.A. 2002. Understory vascular plant species diversity in the mixedwood boreal forest of western Canada. Ecol. Appl. **12**: 588–601. doi:10.1890/1051-0761(2002)012[0588:UVPSDI]2.0.CO;2.

Cumming, S.G. 2001. Forest type and wildfire in the Alberta boreal mixedwood: what do fires burn? Ecol. Appl. **11**: 97–110. doi:10.1890/1051-0761(2001)011[0097:FTAWIT]2.0.CO;2.

Curt, T., Schaffhauser, A., Borgniet, L., Dumas, C., Estève, R., Ganteaume, A., Jappiot, M., Martin, W., N'Diaye, A., and Poilvet, B. 2011. Litter flammability in oak woodlands and shrublands of southeastern France. For. Ecol. Manage. **261**: 2214–2222. doi:10.1016/j.foreco.2010.12.002.

DeByle, N.V., Bevins, C.D., and Fischer, W.C. 1987. Wildfire occurrence in aspen in the interior western United States. West. J. Appl. For. **2**: 73–76.

Emmons, H.W. 1964. Fire in the forest. Fire Research Abstracts and Reviews, **5**: 163–178.

Fechner, G.H., and Barrows, J.S. 1976. Aspen stands as wildfire fuel breaks. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, Eisenhower Consortium Bulletin 4.

Fernandes, P.M., and Cruz, M.G. 2012. Plant flammability experiments offer limited insight into vegetation–fire dynamics interactions. New Phytol. **194**: 606–609. doi:10.1111/j.1469-8137.2012.04065.x.

Fonda, R.W. 2001. Burning characteristics of needles from eight pine species. For. Sci. **47**: 390–396.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada, Science and Sustainable Development Directorate, Ottawa, Ontario, Information Report ST-X-3.

Frandsen, W.H. 1973. Effective heating of fuel ahead of spreading fires. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, Res. Pap. INT-140.

Ganteaume, A., Jappiot, M., Lampin-Maillet, C., Thomas, C., and Borgniet, L. 2011. Effects of vegetation type and fire regime on flammability of undisturbed litter in southeastern France. For. Ecol. Manage. **261**: 2223–2231. doi:10.1016/j.foreco.2010.09.046.

Johnson, E.A., Miyanishi, K., and O'Brien, N. 1999. Long-term reconstruction of the fire season in the mixedwood boreal forest of western Canada. Can. J. Bot. **77**(8): 1185–1188. doi:10.1139/b99-110.

Johnson, E.A., Miyanishi, K., and Bridge, S.R.J. 2001. Wildfire regime in the boreal forest and the idea of suppression and fuel buildup. Conserv. Biol. **15**: 1554–1557. doi:10.1046/j.1523-1739.2001.01005.x.

Kane, J.M., Varner, J.M., and Hiers, J.K. 2008. The burning characteristics of southeastern oaks: discriminating fire facilitators from fire impeders. For. Ecol. Manage. **256**: 2039–2045. doi:10.1016/j.foreco.2008.07.039.

Kreye, J.K., Varner, J.M., and Knapp, E.E. 2012. Moisture desorption in mechanically masticated fuels: effects of particle fracturing and fuelbed compaction. Int. J. Wildland Fire, **21**: 894–904. doi:10.1071/WF11077.

Larsen, C.P.S. 1997. Spatial and temporal variations in boreal forest fire frequency in northern Alberta. J. Biogeogr. **24**: 663–673. doi:10.1111/j.1365-2699.1997.tb00076.x.

Latham, D., and Williams, E. 2001. Lightning and forest fires. *In* Forest fires: behavior and ecological effects. *Edited by* E.A. Johnson and K. Miyanishi. Academic Press, New York. pp. 376–418.

Leonard, S. 2009. Predicting sustained fire spread in Tasmanian native grasslands. Environ. Manage. **44**: 430–440. doi:10.1007/s00267-009-9340-6.

Martin, R.E., Gordon, D.A., and Gutierrez, M.A. 1994. Assessing the flammability of domestic and wildland vegetation. *In* Proceedings 12th Conference on Fire and Forest Meteorology, 26–28 October 1993, Jekyll Island, Georgia. Society of American Foresters, Bethesda, Maryland.

Miller, C., and Urban, D.L. 2000. Connectivity of forest fuels and surface fire regimes. Landsc. Ecol. **15**: 145–154. doi:10.1023/A:1008181313360.

Minnich, R.A. 2001. An integrated model of two fire regimes. Conserv. Biol. **15**: 1549–1553. doi:10.1046/j.1523-1739.2001.01067.x.

Moritz, M.A., Keeley, J.E., Johnson, E.A., and Schaffner, A.A. 2004. Testing a basic assumption of shrubland fire management: how important is fuel age? Front. Ecol. Environ. **2**: 67–72. doi:10.1890/1540-9295(2004)002[0067:TABAOS]2.0.CO;2.

Nelson, R.A., Jr. 2003. Reaction times and burning rates for wind tunnel headfires. Int. J. Wildland Fire, **12**: 195–211. doi:10.1071/WF02041.

Ormeño, E., Céspedes, B., Sánchez, I.A., Velasco-García, A., Moreno, J.M., Fernandez, C., and Baldy, V. 2009. The relationship between terpenes and flammability of leaf litter. For. Ecol. Manage. **257**: 471–482. doi:10.1016/j.foreco.2008.09.019.

Owens, M.K., Lin, C.D., Taylor, C.A., and Whisenant, S.G. 1998. Seasonal patterns of plant flammability and monoterpenoid content in *Juniperus ashei*. J. Chem. Ecol. **24**: 2115–2129. doi:10.1023/A:1020793811615.

Plucinski, M.P., Anderson, W.R., Bradstock, R.A., and Gill, A.M. 2010. The initiation of fire spread in shrubland fuels recreated in the laboratory. Int. J. Wildland Fire, **19**: 512–520. doi:10.1071/WF09038.

Rothermel, R.C. 1972. A mathematical model for predicting fire in wildland fuels. USDA Forest Service, Ogden, Utah, Res. Pap. INT-115.

SAS Institute Inc. 2008. Statistical analysis system. Version 9.2. SAS Institute Inc., Cary, North Carolina.

Scarff, F.R., and Westoby, M. 2006. Leaf litter flammability in some semi-arid Australian woodlands. Funct. Ecol. **20**: 745–752. doi:10.1111/j.1365-2435.2006.01174.x.

Strauss, R.A., Bednar, L., and Mees, R. 1989. Do one percent of forest fires cause ninety-nine percent of the damage? For. Sci. **35**: 319–328.

Susott, R.A. 1982. Characterization of the thermal properties of forest fuels by combustible gas analysis. For. Sci. **28**: 404–420.

Sylvester, T.W., and Wein, R.W. 1981. Fuel characteristics of Arctic plant species and simulated plant community flammability from Rothermel's model. Can. J. Bot. **59**: 898–907. doi:10.1139/b81-125.

Tachajapong, W., Lozano, J., Mahalingam, S., Zhou, X., and Weise, D.R. 2009. Experimental and numerical modeling of shrub crown fire initiation. Combust. Sci. Technol. **181**: 618–640. doi:10.1080/00102200802693617.

Tymstra, C., McGregor, C., Quintilio, D., and O'Shea, K. 1998. Is fire a wildcard in Alberta's protected areas strategy for forest conservation? *In* Linking Protected Areas with Working Landscapes Conserving Biodiversity, Proceedings of the Third International Conference on Science and Management of Protected Areas, 12–16 May 1997, Calgary, Alberta. *Edited by* Neil W.P. Munro and J.H. Martin Willison. The Science and Management of Protected Areas Association, Wolfville, Nova Scotia. pp. 542–551.

Vaz, G.C., André, J.C.S., and Viegas, D.X. 2004. Estimation of the radiation extinction coefficient of natural fuel beds. Int. J. Wildland Fire, **13**: 65–71. doi:10.1071/WF03009.

Weir, J.M.H., Johnson, E.A., and Miyanishi, K. 2000. Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. Ecol. Appl. **10**: 1162–1177. doi:10.1890/1051-0761(2000)010[1162:FFATSA]2.0.CO;2.

Weise, D.R., Zhou, X., Sun, L., and Mahalingham, S. 2005. Fire spread in chaparral — 'go or no-go?' Int. J. Wildland Fire, **14**: 99–106. doi:10.1071/WF04049.

Williams, F.A. 1982. Urban and wildland fire phenomenology. Prog. Energ. Combust. Sci. **8**: 317–354. doi:10.1016/0360-1285(82)90004-1.

Wilson, R.A., Jr. 1985. Observations of extinction and marginal burning states in free burning porous fuel beds. Combust. Sci. Technol. **44**: 179–193. doi:10.1080/00102208508960302.

Wright, J.G., and Beall, H.W. 1934. Seasonal vegetation and forest fire hazard. Pulp and Paper Magazine of Canada, **35**: 259–261.

Zhou, X, Weise, D., and Mahalingam, S. 2005. Experimental measurements and numerical modeling of marginal burning in live chaparral fuel beds. Proceedings of the Combustion Institute, **30**: 2287–2294. doi:10.1016/j.proci.2004.08.022.

Appendix A

Table A1. Supplementary fuel particle surface-area-to-volume ratio measurements (m^{-1}). Included are data for aspen and aspen and alder foliage used in single fuel type burns, fuel types for which unique measurements were not made for all beds. Measurements are also shown for needle litter used in mixed beds. White spruce needles were separated from moss beds. Replication is the number of beds on which measurements were made.

Fuel type	No. of samples	Mean	Minimum	Maximum	SD
Aspen litter	16	13 204	7958	17 786	3285
Aspen and alder litter	7	14 239	12 436	19 188	2268
White spruce needles	5	11 413	10 040	12 279	831
Jack pine needles	18	6482	5987	6826	307