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Surface Fire Extinction in Mixedwood Boreal Forest Fuels

by

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EXECUTIVE SUMMARY

We use a surface-fire extinction index and weather data from periods during which large fires made runs to ask whether surface fuels in aspen and conifer stands in the Saskatchewan mixedwood boreal forest differ in their propensity to carry surface fires. The extinction index is a ratio of a heat source and heat sink term and is calibrated with 430 laboratory test burns. The heat source term includes the heat generated during the combustion process and fuel-bed surface area (a measure of the total surface area in the fuel bed). The heat sink term includes the energy required to raise the fuel's temperature, the energy required to evaporate moisture in the fuel, and the fraction of the fuel mass that is raised to ignition at any given time. As suggested by theory, small changes in fuel conditions meant the difference between fires spreading and fires going out. Surface fuels were sampled in 56 stands spanning the range in upland fuel variability in the mixedwood boreal forest of Saskatchewan. Dead-fuel moisture was estimated from fuel-drying models and weather data for periods during large-area-burned years when large fires made runs. We assume that it is during these periods (when the vast majority of forest area burns) that fuel differences have the potential to cause large effects on landscape-level patterns of burning. Aspen stands ≥30 years-since-last-fire were no less likely to carry surface fires than conifer-dominated stands. The probability of fire spread was low in recently burned stands but increased rapidly with time-since-fire, particularly in stands dominated by aspen and in stands dominated by mixtures of two or more of the following species: aspen, balsam poplar, white spruce, balsam fir, birch, and black spruce. Stands dominated by jack pine or black spruce, and stands with a mixture of these two species, would appear to require the longest time-since-fire to support a surface fire. Our results suggest that increasing aspen dominance on the mixedwood boreal landscape is not likely to be effective at reducing area burned through fire extinction.

INTRODUCTION

A key goal of the Sustainable Forest Management Network is to develop a better understanding of how to mimic natural disturbances (e.g., fire) in forest management practices. We currently know something about the spatial mosaic of stand ages in the mixedwood boreal (e.g., Johnson et.al. 1995, Weir et al. 2000) and the temporal patterns in fire frequency and area burned (e.g., Stocks and Street 1983, Flannigan and Wotton 1991, Stocks 1991, Bergeron and Archambault 1993, Nash and Johnson 1996, Reed et al. 1998) in Canadian boreal forests. However, little is known about surface-fire extinction in fires despite their importance in determining the landscape mosaic of stand ages. We use mechanistic models to guide our study of surface-fire extinction.

Forest managers need to know how fuel differences among stands affect extinction of surface fires. Aspen fuels are widely thought to cause surface-fire extinction more readily than conifer fuels (e.g., Fechner and Barrows 1976, DeByle et al. 1987). We use a surface-fire extinction index based on an energy balance to address two questions. First, do aspen stands have surface-fuel characteristics that would cause surface-fire extinction at lower moisture levels than in conifer stands? If so, do these surface-fuel differences matter when considered in the context of weather during periods in which the vast majority of area burned?

MODELS AND METHODS

Theory suggests that surface-fire extinction occurs abruptly when fires are burning under marginal conditions (Figure 1). A given burning rate requires a certain amount of heat from combustion (Q_R). The (net) heat provided (Q_P) to the fuel in front of the flames for a given burning rate is, in turn, determined by heat transfer from combustion (e.g., radiation from the over-bed flame, radiation through the fuel bed, and convection) and heat losses from the unburned fuel. The heat provided curve (Q_p) is nonlinear because at low combustion rates, flames are small and radiate minimally while, at high combustion rates, heat losses from the fuel from convection and re-radiation are large. Two scenarios are outlined in the figure. In the first, the energy required line (Q_{R1}) intersects the energy provided curve (Q_p) at a high burning rate, resulting in steady fire spread because any random excursion from the intersection (e.g., energy required increases) is buffered by the feedback between the burning rate and heat provided to the fuel (e.g., an increase in energy required results in a drop in heat provided). In the second scenario, the heat required line (Q_{R2}) is tangent to the heat provided curve. The tangency defines an unstable burning regime (the extinction threshold) in which any random excursion below the point of tangency (e.g., a drop in energy provided) results in extinction. Thus, extinction is not expected to be a gradual process, but should occur more as a step function. Given variability in fuel-bed properties, we use a logistic function (that can approach a step function) to summarize our extinction data.

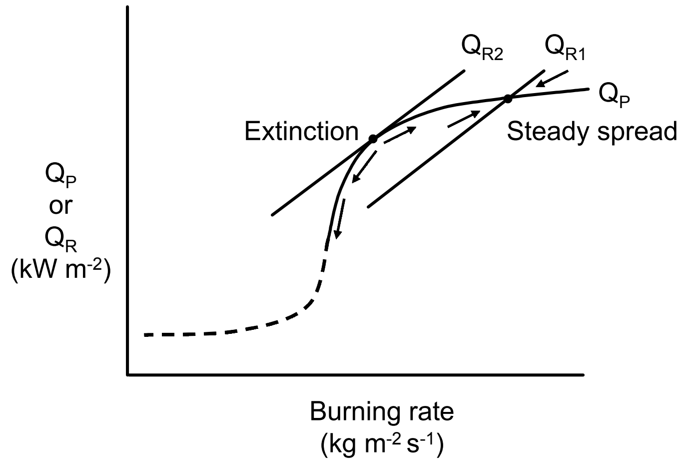

Figure 1. Conceptual diagram of fire extinction. Functions describing heat required to achieve a given burning rate (Q_R) and heat provided to unburned fuel at that burning rate (Q_P) are shown. The two burning rate functions might be characteristic of low (Q_{R1}) and high fuel moisture (Q_{R2}). The tangency point is unstable and defines the extinction limit for the fuel bed.

The surface-fire extinction index used here is based on a heat budget defined by the ratio of a heat source and a heat sink and calibrated with data from 430 laboratory burns. Small fuel beds (30 cm wide, 40 cm long) were ignited at one end with a propane torch and whether the fire spread across 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 fraction of the fuel bed volume occupied by fuel).

The surface-fire extinction index as defined by Wilson (1985) is:

$$n_x = \frac{(h_v \rho_b)^a S^b}{(Q_T \varepsilon \rho_b)^c}.$$

In the heat source term (numerator), h_v is the heat of combustion of volatiles (kJ kg^{-1}), ρ_b is the fuel bed bulk density (kg m^{-3}), and S is the fuel bed surface area (dimensionless). The a and b

are determined from data (see below). The fuel bed surface area is defined as:

$$\sigma\beta\delta$$

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 total heat output from the fuel bed. The amount of surface area in the fuel bed relates to how effectively the fuel bed absorbs radiation from combustion.

In the heat sink (denominator), Q_T (kJ kg^{-1}) is the heat required to vaporize moisture in the fuel and to raise the fuel's temperature to ignition, ε is the effective bulk density, and the exponent *c* is determined from data. The effective bulk density is the fraction of the fuel mass that is undergoing pyrolysis at any given time. The effective bulk density is unity for the finest fuels and is estimated from the equation of Frandsen (1973):

$$\varepsilon = \exp\left(-\frac{453}{\sigma}\right).$$

The exponents in the extinction index were calculated from a logistic regression:

$$P_s = \left(1 + \exp\left[-\left(a\ln(h_v\rho_b) + b\ln(S) - c\ln(Q_T\varepsilon\rho_b)\right)\right]\right)^{-1}$$

where P_s is the probability of flame spread across an experimental fuel bed.

Fuel-bed surface area and bulk densities of the herb and litter layers were estimated using methods in Brown et al. (1982) in 56 upland stands in Prince Albert National Park, Saskatchewan, and the surrounding Weyerhaeuser Forest Management Area. We sampled across the entire upland moisture and nutrient gradient to ensure that the stands spanned the range of variability in tree-species composition (see Bridge and Johnson 2000). We also sampled across the time-since-fire gradient, from 2 to 226 years (Weir et al. 2000). Stands were divided into those ≤12 years since-last-fire and those ≥30 years-since-last fire. No stands were available between 12 and 30 years since-last-fire. The older stands were classified by the relative importance of tree species that formed their canopies, the younger stands by their species composition before the fire.

We sampled fuels during May and June because this is the historical fire season in the mixedwood boreal forest (Johnson et al. 1999). No significant changes in live-to-dead fuel ratios were detected during the May to June sample period. Live-fuel moisture was set to values appropriate for conifer, herbaceous, and deciduous foliage and wood (e.g., Bradshaw et al. 1983).

Total heats of combustion and char heats of combustion for the major fuel classes were determined by oxygen bomb calorimetry. Heat of combustion of volatiles was estimated by the following formula:

$$h_V = h_T - h_C C$$

where h_T is total heat of combustion (kJ kg^{-1}), h_C is char heat of combustion (kJ kg^{-1}), and C is char fraction (dimensionless). Char fraction was determined by heating fuels in an inert atmosphere at 10 ºC min^{-1} from ambient to 500 ºC. We used heat of combustion of volatiles (h_v) in the extinction index because it accounted for more of the variance in burn probability than either total or char heat of combustion.

The moisture of fine, dead fuels varies over short time scales (e.g., hours and days) while fuel characteristics such as chemical properties, fuel loading, and average fuel particle surface-area-to-volume ratios vary over longer time scales (e.g., years to decades). Clearly, not all of the substantial variation in fuel moisture is relevant to understanding the effects of fuel variability on surface-fire extinction because, at minimum, fires have to be burning somewhere on the landscape for fuel variability to have any effect. Further, we assume that, if aspen stands have surface-fuel characteristics that increase the likelihood of surface-fire extinction relative to conifer stands, those differences will have the greatest potential for affecting where fires spread and where they go extinct during periods when the majority of forest area burns. In contrast, there would appear to be little scope for large effects of fuel differences on patterns of burning during periods when area burned is small. A handful of large fires that occur during occasional years (large-area-burned years, Figure 2) accounts for the vast majority of area burned (Strauss et al. 1989, Johnson et al. 1998). We use only weather during these periods in our analyses of the effects of fuel differences on surface-fire extinction. Dead-fuel moisture was estimated from fuel-drying models following methods of Bradshaw et al. (1983) and Van Wagner (1987). In the fuel-drying models, we used standard observations from the Environment Canada or Saskatchewan Environment and Resource Management (SERM) weather station nearest each of a sample of large fires (N = 18). These fires burned between 25,000 and 301,000 ha south of latitude 57 in Saskatchewan during the large-area-burned years of 1981, 1993, 1995, and 1998. Weather from the one to two periods during which these fires made runs was used in the models. Fire behavior information was from SERM records.

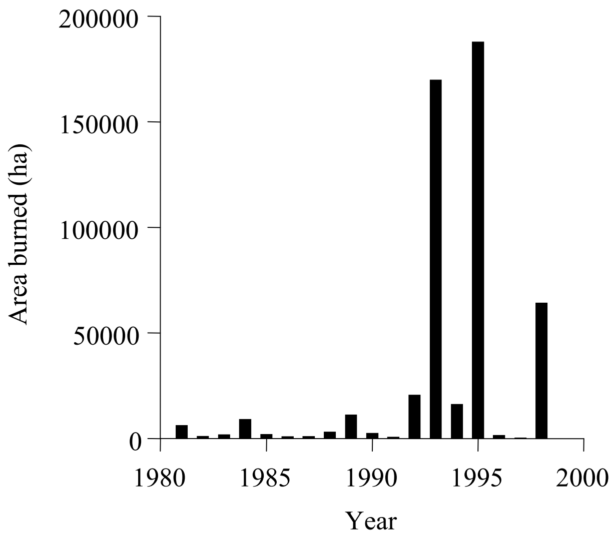

Figure 2. Area burned during the spring fire season in the mixedwood boreal region of Saskatchewan from 1981 to 1998 (data from Saskatchewan Environmental Resource Management).

SUMMARY OF DATA ANALYSIS AND MANAGEMENT APPLICATIONS

As expected from theory, extinction occurred relatively abruptly with small changes in fuel conditions (Figure 3). Furthermore, the curves fit to individual fuel types approximate a step function. The fact that the extinction index does not collapse the data from all fuel types into a single step-like function indicates that it does not capture all relevant processes sufficiently. We suspect that the fuel bed surface area is an inadequate index of such things as radiation absorption and air flow through the fuel bed; i.e., a fuel bed surface area is not the same for flat plates (leaves), cylinders (needles, twigs), and more complex shapes (moss).

Surface fires were predicted to spread across all upland mixedwood boreal forest stands except those that had burned most recently (Figure 4). There were no apparent differences among aspen and conifer stands in their propensity to carry a fire. These results imply that increasing aspen dominance on the mixedwood boreal forest landscape may not be effective as a strategy to encourage fire extinction. In fact, recently burned stands dominated by aspen accumulate surface fuel biomass quickly because of fast regrowth and, thus, these stands would tend to facilitate fire spread relative to stands dominated by jackpine and black spruce (Figure 5).

We caution that the recently burned stands in our sample had not experienced a short fire cycle as would be the case under frequent prescribed burning. Frequent prescribed burning would be expected to have large effects on the herb layer (e.g., increases in grass and herb biomass) that would render invalid any extrapolation of our results.

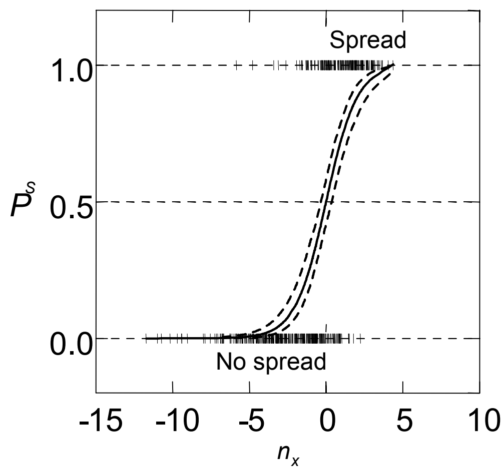

Figure 3. Probability of fire spread across 430 experimental fuel beds (P_S) as a function of the extinction index (n_x). The fitted values (solid line) and their 95% confidence interval (dotted lines) were estimated by logistic regression.

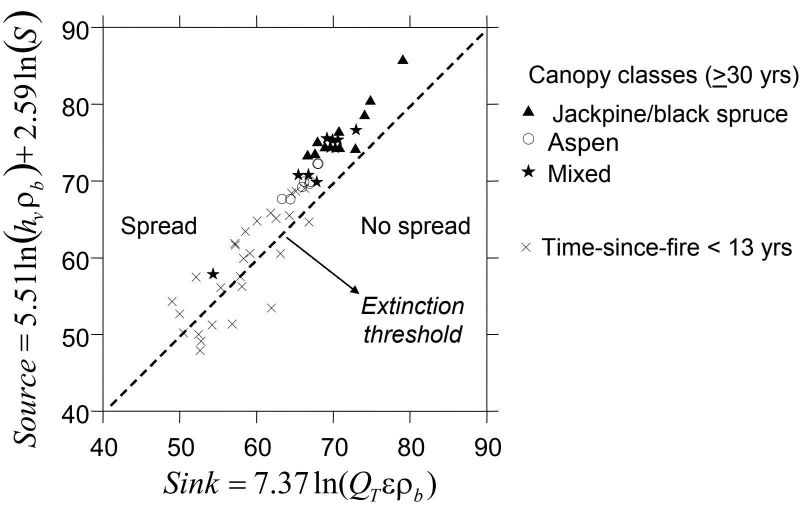

Figure 4. Mixedwood boreal forest stands in source sink-space during periods in which large fires made runs. The extinction threshold corresponds to a spread probability of 0.5 as calculated from laboratory test burns, field data, and weather during periods when large fires made runs. The transition between low and high spread probabilities is abrupt (not shown). Canopy classes for stands >30 years-since-last-fire are given.

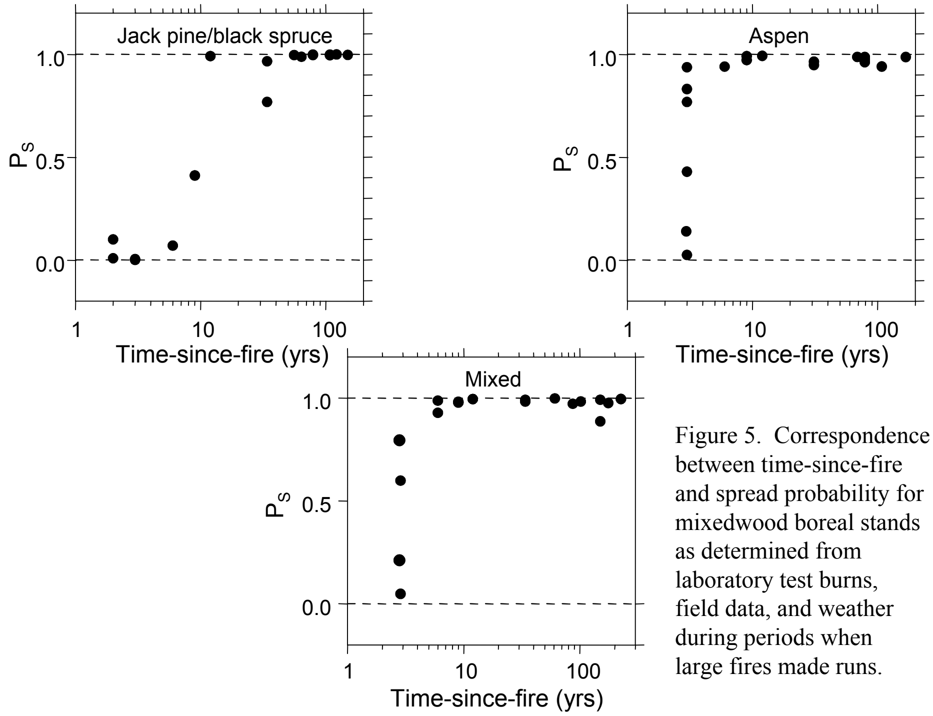

Figure 5. Correspondence between time-since-fire and spread probability for mixedwood boreal stands as determined from laboratory test burns, field data, and weather during periods when large fires made runs.

There have been suggestions by forest managers (e.g., Tymstra *et al*. 1997) that increasing aspen abundance on mixedwood boreal landscapes would reduce the area burned. However, based on our empirical combustion studies, aspen fuels do not exhibit an increased propensity for surface fire extinction when compared to other fuel types. Results from statistical studies of the landscape age patterns in the refereed literature are mixed in terms of differences among deciduous stands and various conifer stand types in burning probabilities. Larsen (1997) found that aspen stands did not have the lowest probability of burning in Wood Buffalo National Park. In contrast, Cumming (2001) found that the lowest burn probabilities were associated with deciduous stands in Alberta. Both studies have the same shortcoming in lacking a mechanistic explanation based on combustion processes.

Some the of uncertainty in our results stems from using the fine-fuel moisture code (FFMC), a model that does not provide spatially-explicit fuel moisture estimates (Van Wagner 1987). The FFMC may not capture fuel drying dynamics properly in aspen-dominated stands because it does not consider increased forest-floor radiation under leafless aspen canopies, higher drying rates of aspen litter compared with conifer needles (Anderson 1990), and the effect of moist soils characteristic of aspen-dominated stands (Bridge and Johnson 2000). The first two factors would tend to cause the FFMC to overestimate aspen litter moisture while the latter would cause underestimates of aspen fuel moisture.

CONCLUSIONS

All stands $\geq$30 years-since-last fire, regardless of canopy composition, were predicted to carry a surface fire during large-area-burned years when large fires made runs. We assume that it is during periods when large fires made runs that fuel differences would have the greatest potential to affect landscape-level patterns of burning. Recently burned stands dominated by aspen before the last fire were predicted to carry a surface fire sooner than jackpine and black spruce stands. These results cast doubt on the utility of increasing aspen abundance on mixedwood boreal landscapes as a means of reducing area burned. However, our present understanding of fire extinction processes is still very limited.

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