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Using Modeled Surface and Crown Fire Behavior Characteristics to Evaluate Fuel Treatment Effectiveness: A Caution

Miguel G. Cruz, Martin E. Alexander, and Jelmer E. Dam

The relative variation in predicted fireline intensity and the wind speed thresholds for the onset of crowning and active crown fire spread in a lodgepole pine (*Pinus contorta* Dougl. ex Loud.) stand subjected to a commercial thinning operation were examined. This involved seven distinct scenarios, each with different assumptions regarding fine dead fuel moisture contents and fire behavior models. This case study illustrates that widely varying results can be expected, depending on how the environmental inputs are handled and which fire behavior characteristic is analyzed.

Keywords: active crown fire spread, fire behavior model, fireline intensity, lodgepole pine, onset of crowning

Fire behavior modeling systems are commonly used to judge the impacts or effectiveness of silvicultural fuel treatments in modifying potential fire behavior in both fire management and fire research (Johnson and Peterson 2005). The ability to mathematically model potential wildland fire behavior with respect to fuel treatments or other fire management applications was not possible until the mid to late 1970s (Anderson 1974, Brown 1974a, Roussopoulos and Johnson 1975, Roussopoulos 1978). Earlier assessments relied entirely on fuel quantification coupled with the judgment of the user (e.g., Brown 1965, Crosby and Loomis 1967, Sando and Wick 1972, Miller and Schwandt 1979).

At present, the ability to quantitatively assess both surface and crown fire potential exists. The fire behavior simulation software tools (McHugh 2006, Andrews 2007) available to fire and land managers allow them to calculate a number of fire behavior characteristics that are relevant to gauging the effect of fuel modification on the "flammability" (wildland fire potential) of a particular fuel complex. Fireline intensity (the energy release rate per linear segment of fire front) (Byram 1959) is, for example, related to the flame dimensions of an advancing fire front and hence the difficulty of controlling a wildfire, maximum spotting distances, and the onset of torching and crowning and to the height of lethal crown scorch (Alexander 2000, Alexander and Cruz 2012).

Given the changes in fire behavior that occur with the onset of crowning, namely the abrupt increase in the rate of fire spread and fireline intensity, another metric favored by managers and researchers is the threshold wind speed (e.g., Duveneck and Patterson 2007) that cause a surface fire to transition to an active crown fire (Van Wagner 1977). In this approach to assessing crown fire potential, all environmental conditions but wind speed are held constant, and fuel moisture contents are selected on the basis of a certain percentile associated with the local fire weather station climatology. For a given stand structure, the model is then used to find the wind speed value for the corresponding crown fire behavior transition point.

Cruz et al. (2003b) showed through a sensitivity analysis how some modeling systems used for simulating fire behavior respond differently to the same inputs. That study highlighted the restrictions of current fire behavior modeling systems and the dangers of misinterpretations that can arise during simulations if the user does not have a clear understanding of two factors: the relationships embodied in the models and the sensitivity of predictions to changes

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Affiliations: *Miguel G. Cruz (miguel.cruz@csiro.au), CSIRO Ecosystem Sciences, Canberra, ACT, Australia. Martin E. Alexander (mea2@telus.net), University of Alberta, Department of Renewable Resources, Edmonton, AB, Canada. Jelmer E. Dam (jelmerdam@hotmail.com), Brandweer Midden Fryslân, Leeuwarden, The Netherlands.*

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; cubic meters (m^3): 1 m^3 = 35.3 ft^3; hectares (ha): 1 ha = 2.47 ac; kilograms (kg): 1 kg = 2.2 lb.

Table 1. Brief summary of the fire behavior models used in the present study.

Model	Primary model outputs	Model description	Model inputs
Rothermel (1972)	Surface fire rate of spread and fireline intensity	A semiempirical surface fire spread model developed primarily from laboratory experiments in homogeneous dead fuels and extended to apply to mixtures of dead and live fuels; model is the basis of operational fire danger rating and fire behavior prediction systems in the United States	Fuel model (Anderson 1982, Burgan and Rothermel 1984) Fuel moisture by fuel size class and condition (i.e., live and dead) Midflame wind speed (Andrews 2012)
Cruz et al. (2004)	Likelihood of crown fire occurrence	Empirically based logistic model that predicts the probability (0–100%) of crown fire occurrence; model was developed from data set of experimental surface (n = 34) and crown fires (n = 37) in conifer forests from Canada, Australia, and Europe	Fine dead fuel moisture 10-m open wind speed Canopy base height Surface fuel consumption
Cruz et al. (2005)	Active crown fire rate of spread	Empirically based fire spread model for active crown fires in conifer forests developed from experimental crown fire data set (n = 24) covering a wide range of Canadian coniferous fuel complexes	Fine dead fuel moisture 10-m open wind speed Canopy bulk density
Van Wagner (1977)	Critical minimum spread rate for active crowning	Semiempirical model describing the threshold for active crown fire propagation; model based on heat balance formulation parameterized with data from experimental crown fire observations (n = 3)[a]	Canopy bulk density

[a]The robustness of the model has been confirmed by Cruz and Alexander (2010).

in model inputs—the proverbial "black box." Proper consideration of the simplifying assumptions associated with the underlying models that comprise a given modeling system and their adequacy to a particular situation must be accounted for to produce realistic simulations and make the outputs relevant in supporting management decisions.

The present study, however, serves to illustrate how different fire behavior models and the manner in which the inputs, e.g., fuel moisture content, are handled can produce widely varying results when used to evaluate the effectiveness of fuel treatments. Several different environmental inputs (fire behavior modeling system scenarios, involving three different aspects of fire behavior), namely, fireline intensity, the onset of crowning, and active crown fire spread, involving a lodgepole pine (*Pinus contorta* Dougl. ex Loud.) stand are examined. A general familiarity with the concepts involved with fire behavior models and modeling systems (Table 1) used in the case study methodology on the part of the reader is presumed. For further information, refer to Cruz and Alexander (2010) and Alexander and Cruz (2011).

Methods

Fuel and Stand Characteristics

The case study presented here is based on data collected by Dam (1999) in a 36-ha lodgepole pine stand in central Alberta, Canada. The treated portion of the stand consisted of a commercial thinning from below as part of a larger silvicultural study (Krygier 1998), as opposed to a fuel management objective, undertaken by Millar Western Forest Products Limited based in Whitecourt, Alberta, Canada. The commercial thinning would have been undertaken to extract wood fiber and also to improve the growth of the subsequent stand. Stand and fuel characteristics for the untreated (control) and treated areas are presented in Table 2.

Weather Conditions

The analysis of potential fire behavior in treated and untreated portions of the stand relies on estimated base fine dead fuel moisture content, taking into account the 97th percentile of weather conditions as sampled on site by Dam (1999) during the three summers of 1997–1999. The 97th percentiles of air temperature and relative humidity were 29.0° C and 24%, respectively. The Rothermel et al.

Table 2. Stand and fuel complex description for treated and untreated portions of a lodgepole pine stand in central Alberta, Canada.

Item	Treated	Untreated
Stand descriptors		
Tree density (live stems/ha)	1,550	4,050
Tree height (m)	14.9	14.2
Basal area (m^2/ha)	25.5	56.5
Canopy length (m)	5.3	5.9
Surface fuel stratum[a]		
1-h TL fuel load (t/ha)	0.8	0.3
10-h TL fuel load (t/ha)	1.1	0.5
100-h TL fuel load (t/ha)	4.9	3.8
1,000-h TL fuel load (t/ha)	12.2	13.7
Litter fuel load (t/ha)	4.0	4.0
Fuel depth (cm)	13.6	8.0
Canopy fuel stratum		
Canopy base height (m)	9.9	9.2
Fuel strata gap (m)[b]	3.6	2.8
Canopy bulk density (kg/m^3)	0.18	0.35
Canopy cover (%)	62	100

Adapted from Dam (1999).
[a]The dead-down woody fuel time lags (TLs) correspond to roundwood diameters of (from Brown 1974b): <0.64 cm (1-h TL), 0.64–2.5 cm (10-h TL), 2.5–7.6 cm (100 h TL), and >7.6 cm (1000-h TL).
[b]As per Cruz et al. (2004).

(1986) fine fuel moisture content model was used to estimate the moisture content of the needle litter and the dead, small diameter twigs. Dam (1999) found significant differences in dead fuel moisture content sampled in the control and treated stands. Needle litter on the treated stand had on average a moisture content 2.6 percentage points lower than that found on the control stand (Table 3). Dam (1999) did not find significant changes in the in-stand wind speed between the treated and untreated blocks during the summer months.

Fire Behavior Metrics

Three distinct metrics were used to quantify fire behavior potential. These were the following: the fireline intensity associated with a spreading surface fire as predicted by the Rothermel (1972) model; the wind speed required for crown fire initiation using the Cruz et al. (2004) model; and the wind speed required to sustain fully developed crowning using the Cruz et al. (2005) active crown fire rate of

Table 3. Summary of fine dead fuel moisture and fire behavior metric assigned to each environmental input-fire behavior model scenario.

Scenario no.	Environmental-fire behavior model scenario description	Fine dead fuel moisture (%) Treated	Fine dead fuel moisture (%) Control	Metric used to quantify fire behavior
1	Application of the Rothermel (1972) surface fire spread model with custom fuel models (Burgan and Rothermel 1984) considering changes in fuelbed structure induced by the commercial thinning (Dam 1999) and assuming identical fine dead fuel moisture and in-stand wind speed in both the untreated and treated areas	4.0	4.0	Fireline intensity
2	Same as scenario 1 but modeling changes in fine dead fuel moisture by application of the Rothermel et al. (1986) fine dead fuel moisture model (i.e., the moisture content of the fine dead fuels in the treated portion of the stand was predicted to be 0.5% lower than in the control portion)	3.5	4.0	Fireline intensity
3	Same as scenario 1, but considering the differences in fine dead fuel moisture as sampled by Dam (1999) at the study sites (i.e., fine dead fuel moistures in the surface fuel stratum of the treated portion of the stand were consistently lower, averaging 2.6% for the needle litter and 2.0% for the dead, small diameter twigs)	4.0	6.5	Fireline intensity
4	Wind speed threshold for crowning based on the Cruz et al. (2004) crown fire occurrence model and considering the same fine dead fuel moisture level as for scenario 1	4.0	4.0	Wind speed for onset of crowning
5	Same as scenario 4 but with the same fine dead fuel moisture as in scenario 3	4.0	6.5	Wind speed for onset of crowning
6	Wind speed threshold for active crowning as described by Scott and Reinhardt (2001) but using the Cruz et al. (2005) model considering the same fine dead fuel moisture levels as for scenario 1	4.0	4.0	Wind speed for active crown fire spread
7	Scenario 6 but with fine dead fuel moisture as in scenario 3	4.0	6.5	Wind speed for active crown fire spread

spread model, coupled with Van Wagner's (1977) concept of a critical minimum spread rate for active crown fire (R_o, m/min)

$$R_o = 3.0 \div \text{CBD} \quad (1)$$

where CBD is the canopy bulk density (kg/m^3), which in turn represents the available canopy fuel load (kg/m^2) divided by the depth of the canopy fuel layer, i.e., the average stand height less the canopy base height (CBH, m) (Cruz et al. 2003a). Active crowning is expected to occur when the rate of fire spread after the onset of crowning is greater than or equal to R_o.

Seven distinct environmental input-fire behavior model scenarios were considered. The fine dead fuel moistures associated with the seven scenarios and the metric used in the assessment of potential fire behavior are summarized in Table 3.

The changes in fire behavior potential for the various scenarios were assessed by calculating the percent change in the fire behavior metric relative to the control situation. A positive percent variation indicates that the thinning resulted in an increase in fire behavior potential relative to the control or no-thinning situation. Conversely, a negative percent variation indicates that the treatment reduced the potential fire behavior by the indicated percentage.

Results and Discussion

The thinning from below treatment removed 62% of the trees in the stand and reduced its basal area to approximately half of the original value (Table 2). From a fire behavior assessment standpoint, the main impact of the thinning in the surface fuel layer was to triple the load of fine woody fuels (1-hour time lag) and increase fuel bed depth by 70%. The thinning led to a small increase in the CBH (from 9.2 to 9.9 m) and the fuel strata gap (from 2.8 to 3.6 m) as described by Cruz et al. (2004). The CBD was approximately halved, from a relatively high value of 0.35 to 0.18 kg/m^3 (Table 2). Although the thinning did not have the specific aim as a fuel treatment of reducing crown fire potential, the reduction achieved in CBD and increase in CBH would probably lessen the chance of active crowning (Agee and Skinner 2005).

As expected from physical reasoning, the untreated residues from the silvicultural treatment increased the surface fire intensity potential (Alexander and Yancik 1977, Brown and Johnston 1987), but the relative change between the control and treatment depends on the degree of realism that is applied to the scenario (Figure 1). For the scenarios using fireline intensity as the evaluation metric, the simulation with equal fuel moistures results in a 90% increase in fire potential. For scenario 3, use of the average difference in fuel moisture between the control and treated stand resulted in a 160% increase in fireline intensity. These results for scenarios 1 to 3 are independent of wind speed (i.e., the relative changes in fire behavior are maintained across the common range of wind speeds).

The changes in crown fire initiation potential as quantified by the wind speed required for crown fire occurrence are not so readily obvious (i.e., scenarios 4 and 5), in part because the treatment did not result in large changes in the CBH or fuel strata gap. Whereas scenario 4 indicates a reduction in the likelihood of crown fire occurrence by 22%, the most realistic situation (i.e., scenario 5) points to a modest increase in crowning potential for the treated plot (8% decrease in the wind threshold) that results from the heavier surface fuel load and lower fuel moisture in the treated stand. For the simulations considering crown fire propagation, the reduction in CBD due to the thinning treatment resulted in increases of 154% (scenario 6) and 51% (scenario 7) in the wind speed threshold for

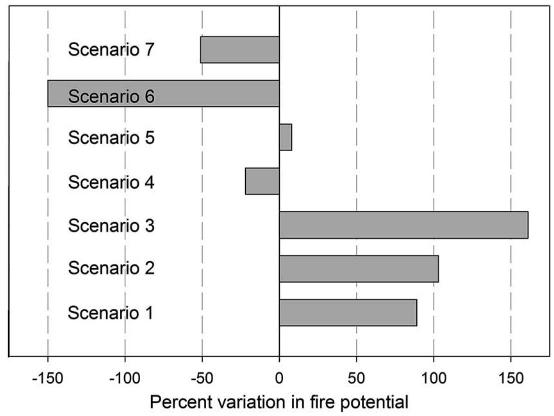

Figure 1. Variations in fireline intensity (scenarios 1–3), onset of crowning (scenarios 4 and 5), and active crown fire spread (scenarios 6 and 7) between commercially thinned (i.e., treated) and corresponding unthinned (i.e., control) areas of a lodgepole pine stand in central Alberta, Canada. Positive values indicate that the commercial thinning increased fire behavior potential, whereas negative values indicate that the fire behavior potential was decreased by the commercial thinning.

active crown fire spread relative to that for the untreated situation, hence a sharp reduction in the potential for active crown fire propagation.

In our study, although the commercial thinning led to a decrease in the likelihood of active crown fire propagation, it also caused a substantial increase in the surface fireline intensity. These outcomes highlight the fact that fuel management was not a direct objective of the thinning treatment. To mitigate the potential in surface fire intensity after thinning treatments, presumably some form of surface fuel modification to reduce the amount of fuel available for combustion is needed (Agee and Skinner 2005) or an alternative is to take the risk that the fuel hazard will eventually abate itself in due course as a result of decomposition and settling (Carlton and Pickford 1982, Christiansen and Pickford 1991). A target fuel treatment prescription would probably increase the CBH and decrease the CBD (Agee and Skinner 2005). This result could be accomplished by removing more trees. The two models for crown fire activity used in this modeling exercise could be used to investigate target stand structures that would meet silvicultural and fuel management prescriptions.

There are two implications emerging from the distinct outcomes shown in Figure 1. The first concerns the decision as to which fire behavior characteristic should be used in evaluating the effects of fuel treatments. This has a strong bearing on calculated fire behavior potential and therefore warrants serious consideration on the part of the analyst. The second involves a decision as to how best to specify the burning conditions associated with a modeling scenario.

Our assessment of fire behavior potential considered the 97th percentile fire weather and fire danger conditions to define a "worst case" situation. One of the drawbacks of this approach is that the simulations capture a sole point in the fire behavior potential spectrum. A fire manager might be more interested in assessing fire potential under more common and not so severe conditions, e.g., conditions in which an initial attack is more likely to be successful (Plucinski 2012) or in which fuel treatments have a higher likelihood of being effective. From a mathematical modeling standpoint, to assess the fire potential of a stand over the full spectrum of fire behavior, the analysis should consider the cumulative distribution of days susceptible to a certain level of fire behavior in lieu of adopting a worst case situation approach (e.g., 97th or 99th percentile fire weather conditions).

Conclusions

As Cruz and Alexander (2010) have pointed out, the fuels management literature abounds with examples of so-called evaluations of fuel treatment effectiveness based on simulations performed using fire modeling systems and assumptions that may not be valid or are otherwise incomplete for various reasons as identified by Keyes and Varner (2006) and Varner and Keyes (2009). In this particular fire behavior modeling case study, the predicted fireline intensity, onset of crowning, and active crown fire spread were shown to vary widely depending on the assumptions used to estimate fuel dryness. Small changes in the estimated fine dead fuel moisture content (i.e., $<$2.5%) can produce widely varying results. This variation is especially relevant when models are used to evaluate the effects of silvicultural fuel treatments due to the effect of the changes in stand structure on the micrometeorological environment.

Evaluating the effectiveness of fuel treatments, however, encompasses more than such mathematical modeling. Personal experience and case history knowledge of experimental fires, operational prescribed fires, and/or wildfires also play a role (Alexander 2007a). Furthermore, a strong sense of social responsibility (Alexander 2007b) and sound professional judgment (Alexander 2009) are considered desirable.

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