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SENSITIVITY ANALYSIS OF A METHOD FOR ASSESSING CROWN FIRE HAZARD IN THE NORTHERN ROCKY MOUNTAINS, USA

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SUMMARY

Van Wagner's two-equation method of linking surface and crown fire behavior predictions has been adapted to the fire behavior prediction system used in the United States. Two ordinal indexes of crown fire hazard — the Torching Index and Crowning Index — were derived from the U.S. adaptation. This paper explores the sensitivity of these indexes to surface fuel, crown fuel, and site characteristics. In the coupled model, the onset of crowning is most-strongly affected by crown base height and surface fuel load. Susceptibility of a stand to active crowning is most-strongly affected by crown bulk density. Implications for crown fire mitigation treatments are discussed.

keywords: fuels, hazard assessment, forest fire behavior, crown fire initiation, fire potential

INTRODUCTION

Wildland fire in a coniferous forest can burn as a slow-spreading, low-intensity surface fire during mild conditions, or as a fast-spreading, high-intensity crown fire during more extreme conditions. Although crown fires constitute a small fraction of all forest fires, they account for a large portion of the area burned. Compared to surface fires, crown fires produce much more smoke, cause more resource loss, remove more nutrients from a site, and increase the threat to life and property. Fire managers need basic tools to assess crown fire hazard and design treatments for its mitigation. The ability to predict the onset of crowning in a forest stand is essential to assessing forest fire hazard.

Van Wagner (1989, 1993) suggests a two-equation system for predicting the onset of crowning and subsequent spread rate — a "lower" equation (or any predictive model) to estimate the spread rate of a surface fire, and an "upper" model to estimate the spread rate of a fully-active crown fire. A transition function is then used to scale between the two spread rate predictions.

This method is used in a portion of the Canadian Fire Behavior Prediction System (Forestry Canada Fire Danger Group 1992). It was also used to couple separate models of surface and crown fire behavior used in the United States (Scott and Reinhardt in preparation). The U.S. adaptation uses the Rothermel model (Rothermel 1972, Albini 1976) for surface fire spread rate, Rothermel's (1991) crown fire spread rate correlation, and a modified version of Van Wagner's (1993) "crown fraction burned" transition function. Rothermel's crown fire correlation is only applicable in the Northern Rocky Mountains and other mountainous areas with similar fuels and climate. Other crown fire models can be substituted as they become available.

From the coupled model, Scott and Reinhardt (in preparation) developed two crown fire hazard indexes to assess any surface/crown fuel complex: the Torching Index (TI), the open (6-meter) windspeed at which some kind of crown fire activity begins, and the Crowning Index (CI), the open windspeed at which active crowning is possible. Due to their emphasis on hazard assessment, the TI and CI are computed for upslope winds, with user-defined surface fuel moisture conditions.

The coupled model has many input factors: fuel model (load, bulk density, surface-area-to-volume ratio, heat content), slope steepness, open windspeed, wind reduction factor, surface fuel moistures, foliar moisture content, crown base height, and crown bulk density. This paper is a sensitivity analysis of the Torching and Crowning Indexes derived from the coupled model. The analysis will indicate which of the factors in the coupled model strongly affect transition to crown fire and which have only a weak effect.

COMPONENTS OF THE COUPLED MODEL

The coupled model of surface and crown fire behavior relies on several underlying models. This section briefly outlines the component models used in the United States. One component is Rothermel's (1972) model of surface fire spread rate. It is well known and will not be discussed here.

Rothermel's crown fire spread rate correlation

Rothermel developed his crown fire spread prediction method by simple linear regression of observed crown fire spread rates with predictions using his surface fire model with Fire Behavior Fuel Model (FM) 10 (Anderson 1982) and a wind reduction factor of 0.4 (based on the U.S. standard height of 6.1-m). He obtained the best fit with a coefficient of 3.34 — that is, crown fire spread rate is 3.34 times the spread rate predicted the surface fire model using FM 10 and a 0.4 wind reduction factor. In this model, crown spread rate varies with the same factors as for surface fires — surface fuel moisture, windspeed, and slope — but not with crown fuel characteristics like foliar moisture content and crown bulk density (*CBD*).

Predicted crown fire spread rate will be used to estimate the mass-flow rate through crown fuels for comparison with a threshold value (see below). Therefore, the predicted crown fire spread rate should not include the effect of medium- or long-range spotting on overall fire growth — it should be an estimate of the spread rate of the flame front itself. Long-range spotting causes new fires that the main fire may never reach. Medium-range spotting causes fires that accelerate and stay ahead of the main fire front, effectively increasing fire's overall spread rate. Short-range spot fires are overrun by the main fire before they can accelerate to a steady-state crown fire.

The Rothermel crown fire spread correlation does not include the effects of long-range spotting, but does include medium-range spotting. Therefore, the Rothermel model of crown fire spread probably overpredicts spread rate of the flame front itself. Until physical models of crown fire spread are available, this probable overprediction can be addressed through the use of a crown fire spread rate adjustment factor (*CSAF*). The user must determine the *CSAF* from judgment and experience. In this analysis a *CSAF* of 0.7 will be used.

The Rothermel crown fire model can be extended to include the effect of foliar moisture content using a spread rate multiplier to account for the effect of moisture on the flame's radiation intensity and on the heat yield of crown fuel (Van Wagner 1989, 1993). The multiplier is the ratio of actual foliar moisture effect (*FME*) to a normal value, FME_o, which is based on the mean *FMC* used in determining the crown fire behavior prediction model. The *FMC* on the fires Rothermel used in his correlation was not documented and undoubtedly varied among fires. An *FMC* of 100 percent, an average value across species and seasons (Brown 1978), will be used as the basis for FME_o in this analysis.

Thresholds for crown fire initiation and sustained spread

The methods presented here are based on Van Wagner's (1977) criteria for crown fire initiation and sustained crown fire spread. Below is a summary of the key points of these criteria. The criteria are discussed more thoroughly elsewhere (Agee 1996, Alexander 1988, Scott and Reinhardt in prep).

Van Wagner (1977) theorizes that crown fuels will ignite when heat supplied by the surface fire raises crown fuels to ignition temperature (after first driving off moisture). He identifies the minimum fireline intensity, $I'_{initiation}$, that will ignite foliage of a given moisture content and height above the ground. Combining Van Wagner's equations, $I'_{initiation}$ (kW m^{-1}) can be expressed

$$I'_{initiation} = \left(\frac{CBH(460 + 25.9FMC)}{100}\right)^{3/2} \qquad (1)$$

where *CBH* is the crown base height (m) and *FMC* is foliar moisture content in percent. For further analysis, $I'_{initiation}$ can be converted to its equivalent critical rate of spread, $R'_{initiation}$, by rearranging Byram's (1959) equation defining fireline intensity, $I = HWR$

$$R'_{initiation} = \frac{60I'_{initiation}}{HPA} \qquad (2)$$

where HPA, the heat per unit area of surface fuels, is the product of heat yield of surface fuels (H) and the weight of fuel consumed in the flaming front (W). In Rothermel's (1972) surface fire model, HPA is a function of fuel characteristics (fuel model) and fuel moisture, but not wind or slope. This crown fire initiation criterion is based on a single observation and has not been well tested, but there is general agreement among researchers that it includes the major variables important in initiating a crown fire.

Van Wagner theorized that solid flames would form in the crowns (active crowning) if a critical horizontal mass-flow rate through the canopy (the product of spread rate and CBD) is exceeded. In uniform stands, CBD is the weight of available crown fuel divided by crown length. Alexander (1988) presents Van Wagner's critical spread rate for active crowning, R'_{active}, as

$$R'_{active} = \frac{3.0}{CBD} \tag{3}$$

where R'_{active} is in m min^{-1} and CBD is in kg m^{-3}. Thus, occurrence of sustained active crowning depends on CBD and potential crown fire spread rate.

Van Wagner (1977) and Alexander (1988) use the criteria for initiation and sustained spread of crown fires to classify a fire as surface, passive crown, or active crown fire.

	$R_{crown} < R'_{active}$	$R_{crown} > R'_{active}$
$I_{surface} < I'_{initiation}$	surface fire	surface fire
$I_{surface} > I'_{initiation}$	passive crown fire	active crown fire

The surface fire intensity criterion determines if some kind of crown fire is possible. If so, the crown spread rate criterion determines if the crown fire is passive or active. The surface intensity criterion can also be expressed in terms of a critical surface fire spread rate (see equation 2 above).

Torching and Crowning Indexes

By coupling the models of surface and crown fire behavior with their respective thresholds we can define two indexes of crown fire hazard. The Torching Index (TI) is the open (6-meter) windspeed at which some kind of crown fire may occur, assuming upslope winds (Scott and Reinhardt in preparation). It is the windspeed at which the predicted surface fire intensity equals the critical intensity for crown fire initiation (that is, $I_{surface} = I'_{initiation}$). Using equation (2), we can also express this equality in terms of surface spread rate ($R_{surface} = R'_{initiation}$). The TI can be found graphically by plotting critical and predicted surface fire spread rate over a range of open windspeeds. The point on the X-axis where the two lines cross is the TI (Fig. 1). A low value of TI indicates high susceptibility to crown fire initiation; a high value indicates low susceptibility.

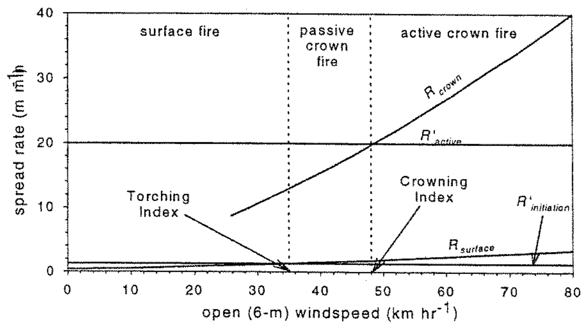

Figure 1. A crown fire hazard assessment chart for the standard inputs shown in Table 1. $R_{surface}$ is from Rothermel's (1972) model, R_{crown} is from his (1991) crown fire correlation, $R'_{initiation}$ is from equations (1) and (2), and R'_{active} is from equation (3). The Torching and Crowning Indexes, as well as regions of surface, passive crown, and active crown fire, are shown on the chart.

Similarly, the Crowning Index (CI) is the open windspeed at which sustained active crowning can be expected — where $R_{crown} = R'_{active}$. The CI can also be determined graphically by plotting predicted (R_{crown}) and critical (R'_{active}) crown fire spread rates over a range of open windspeeds. The point on the X-axis where these two lines cross is the CI (Figure 1). Scott and Reinhardt (in prep) present analytical solutions for both the Torching and Crowning Indexes.

Type of fire can be classified by comparing the open windspeed to the Torching and Crowning Indexes. Van Wagner's original classification is modified to include a "conditional surface fire", the special case when the conditions exist to support an active crown fire but not to initiate a crown fire. In such a case, a new ignition or spreading surface fire is expected to remain a surface fire, but an active crown fire spreading into the stand may not immediately drop to the surface.

	Windspeed < Crowning	Windspeed > Crowning Index
windspeed < Torching	surface fire	conditional surface fire
windspeed > Torching	passive crown fire	active crown fire

With the exception of the conditional surface fire, this classification approach will provide the same results as the Van Wagner classification above. This classification can be visualized graphically on the same chart used to determine the indexes (Fig. 1).

The factors affecting TI are fuel model (load, bulk density, surface-area-to-volume ratio and heat yield), surface fuel moisture, slope, crown base height, foliar moisture content and wind reduction factor. Factors affecting CI are crown bulk density, surface fuel moisture, slope, foliar moisture content, and crown spread adjustment factor. The factors affecting TI and CI do not necessarily vary independently. For example, a decrease in *CBD* (such as from a thinning) may be associated with an increase in wind reduction factor (*WRF*, multiplication factor to adjust open windspeed to midflame) and a decrease in surface fuel moistures. Also, depending on subsequent fuel treatment, thinning may lead to increased surface fuel load.

SENSITIVITY ANALYSIS

This analysis will be based on the following "standard" description of a forest fuel complex (Table 1). If the value of any factor is not being varied in the analysis, it is presumed to be at its standard value. The standard values are only for conducting the sensitivity analysis — they do not represent any particular forest stand or forest stands in general.

Factor	standard value
Fire Behavior Fuel Model	10
Fuel load multiplier	1.0
1-hr dead surface fuel moisture, percent	6
Live surface fuel moisture, percent	117
Slope, percent	20
Crown base height, meters	1.5
Foliar moisture content, percent	100
Wind reduction factor	.12
Crown bulk density, kg m^{-3}	.15
Crown spread rate adjustment factor	0.7

Table 1. Standard values of the input factors to be used in all following examples. Ten-hour timelag fuels are assumed to be 2 percent higher than 1-hr, and 100-hr fuels 2 percent higher than 10-hr.

Using these standard values as a base, the sensitivity of the Torching and Crowning Indexes will be analyzed separately by varying these factors across their "usual" range. For simplicity, ten-hour timelag fuels are assumed to be 2 percent higher than 1-hr, and 100-hr fuels 2 percent higher than 10-hr. The fuel load multiplier adjusts both the loading and fuelbed depth of fuelbed so that bulk density, an important factor in the Rothermel surface fire spread model, is constant. Spread rate varies linearly with this multiplier, but intensity varies with its square. All other attributes of the fuel model (characteristic surface-area-to-volume ratio, heat content, and extinction moisture) are preserved.

Torching Index

For the standard condition described in Table 1 the Torching Index (TI) is 35 — that is, under those conditions, the critical intensity for crown fire initiation is achieved when the open windspeed is 35 km hr^{-1}. All of the factors affecting TI are continuous variables except fuel model.

The sensitivity of TI to surface fuel model and *CBH* is shown in Fig. 2 for the Fire Behavior Fuel Models that commonly have a moderately-dense conifer overstory. As would be expected, the Torching Index increases with increasing crown base height, but at different rates for different fuel models. Of particular interest are the "extremes" of the fuel models — FM 8 (short-needled timber litter) and FM 12 (medium logging slash). The very compact fuelbed of FM 8 produces so little fireline intensity that, even under very windy conditions, only crowns less than one meter from the ground will be ignited. With more moderate winds, crowns must be within about 0.25 m of ground for ignition. In contrast, FM 12 produces enough intensity that crowns as low as 1.5 m can be ignited without any wind, and crowns 6 m above the ground can be ignited if the open wind reaches about 50 km hr^{-1}.

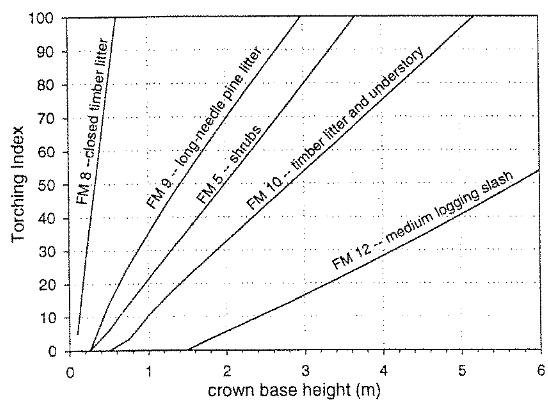

Figure 2. Sensitivity of the Torching Index to crown base base height (CBH) and Fire Behavior Fuel Model (FM) (Anderson 1982).

The remaining factors affecting TI are continuous variables and have a usual range of variability that is commonly associated with crown fire. The "sensitivity" of TI to each factor will be measured by computing the percent change in TI for a one-percentile change in each factor — that is, a change equal to one percent of that factor's usual range. For example, the standard value of *CBH* is 1.5 m and its usual range is taken to be 0.5 to 6 m. A 1 percentile change in its usual range is (6.0-0.5)/100, or 0.055 m. Thus, the sensitivity if TI to *CBH* is the percent change in TI as *CBH* is changed from 1.5 to 1.555 m. This computed sensitivity depends in large part on the values of the remaining factors. "Marginal Sensitivity" is the sensitivity of any factor when all factors are at their "standard" values. "Average Sensitivity" is the mean of sensitivity values computed by individually varying each factor (in 10 percentile increments) across its range. "Maximum Sensitivity" is the highest sensitivity observed in computing the average sensitivity for each factor.

Factor	standard value	usual range	Marginal Sensitivity	average sensitivity	maximum sensitivity	range spread
CBH, meters	1 .5	0.5 - 6.0	5.54	6.23	43.13	96
fuel load multiplier	1.0	0.5 - 1.5	2.00	2.39	17.30	63
WRF	0.12	0.1 - 0.3	1.63	1.55	1.96	17
1-hr fuel moisture, %	6	3-16	1.02	1.18	8.41	18
slope, percent	0	0 - 60	0.79	1.18	16.25	25
FMC, percent	100	70 - 120	0.64	0.77	5.32	14

Table 2. Sensitivity of Torching Index to its input factors. The "usual range" is the range of each input factor that may be associated with crown fire activity. Sensitivity is the percent change in the TI for a 1 percentile change in each factor. Marginal sensitivity is computed with all factors at their standard values. Average and maximum sensitivities are computed by varying all factors across their usual range. Factors are listed in order of decreasing marginal sensitivity. Range spread is the difference between the highest and lowest TI associated with the usual range of each factor.

The effects of each factor on TI can also be analyzed by varying the value of each factor across its usual range — holding all other factors constant at their standard values — and computing the resulting range of TI. A larger range spread indicates stronger sensitivity to that factor.

As indicated by all sensitivity measures in Table 2, *CBH* has the strongest effect on crown fire initiation — small changes in *CBH* result in large changes in TI. This also means that uncertainty in estimating *CBH*, which is quite difficult to measure in most stands, can lead to significant error in predicting the onset of crowning. The level of surface fuel loading also strongly affects TI. Foliar moisture content only weakly affects crown fire initiation in the coupled model.

Depending on which measure of sensitivity is used, the remaining factors area either moderate or weak variables. This simple analysis ignores the interactions among factors, but probably indicates their relative strength under most conditions. A more thorough sensitivity analysis of interactions among the factors is beyond the scope of this paper.

Crowning Index

A similar analysis can be made for the factors affecting the Crowning Index (CI). For the "standard" condition described in Table 1 the Crowning Index is 48 — active crowning is possible above an open windspeed of 48 km hr^{-1}. The usual ranges and effects of all factors affecting CI are shown in Table 3.

Factor	standard value	usual range	Marginal Sensitivity	average sensitivity	maximum sensitivity	Range Spread
CBD, kg m^{-3}	.15	.05 - .35	1.44	1.47	4.06	51
FMC, percent	100	70 - 120	0.64	0.66	0.77	19
CSAF	.7	.5 - 1	0.52	0.53	0.72	15
dead fuel moisture, %	6	3-16	0.42	0.41	0.63	10
slope, percent	20	0 - 60	0.09	0.11	0.32	4

Table 3. Sensitivity of Crowning Index to its input factors. The "usual range" is the range of each input factor that may be associated with crown fire activity. Sensitivity is the percent change in the CI for a 1 percentile change in each factor. Marginal sensitivity is computed with all factors at their standard values. Average and maximum sensitivities are computed by varying all factors across their usual range. Factors are listed in order of decreasing marginal sensitivity. Range spread is the difference between the highest and lowest CI associated with the usual range of each factor.

By all measures of sensitivity, *CBD* appears to be the most important variable in determining a stand's susceptibility to active crown fires, with *FMC* a distant second. Uncertainty in crown fire spread rate (indicated by *CSAF*) appears to be less important in determining active crown fire hazard than *CBD* or *FMC*. This is important because we know there is considerable uncertainty in the Rothermel crown fire correlation. In the coupled model, slope and surface fuel moisture have little effect on CI.

A hidden factor in this analysis is the effect of windspeed on torching and crowning — perhaps the most important factor of all. Windspeed is indicated in the value of TI and CI, so cannot be included in the sensitivity analysis unless a different index is chosen. In fact, windspeed was chosen to be the index because of its high variability and strong effects on torching and crowning.

Managers who wish to reduce crown fire hazard must determine how different fuel treatments affect torching and crowning. This can be done by first simulating the effects of a treatment on the inputs to the coupled model. Fuel treatments that reduce crown fire hazard involve a combination of thinning, pruning, pile burning, broadcast burning, lopping and chipping. The effects of these treatments change over time. For example, a broadcast burn reduces surface fuels immediately after the burn. However, depending on stand structure, resulting mortality and needle scorch may lead to higher fuel load a few years after the burn. As fuels decompose, fuel load may again decrease. Managers must consider the time frame of interest when comparing treatments. The Fire and Fuels Extension to the Forest Vegetation Simulator (Beukema and others 1997) provides guidance for determining the longer-term effects of fuel treatments. The near-term effects of different fuel treatments on fuel parameters are summarized in Table 4. Foliar moisture content is presumed to be independent of fuel treatment.

Fuel treatment	fuel load	dead fuel moisture	crown base height	wind reduction factor	crown bulk density
Overstory thinning	I	D	I or NE	I	D
Understory removal	I		I		D or NE
Pruning	I		I		
Pile burning	D				
whole-tree yarding	D				
broadcast burning	D		I or NE		

Table 4. The immediate-term effects of fuel treatments on factors that affect the Torching or Crowning Indexes. A blank cell in the table indicates there is no effect on that factor. I = increase, D = Decrease, NE = no effect. The whole-tree yarding treatment is only applicable when preceeded by a harvest.

A thinning designed to reduce crown fire hazard will usually raise the effective *CBH*. However, in a partial harvest such as selection or crown thinning, mainly large trees with high crown bases are removed, so the effective *CBH* may not change. Similarly, a broadcast burn will usually increase *CBH* by scorching lower branches. However, a broadcast burn under moderate burning conditions may be patchy and of insufficient intensity to effectively increase *CBH* for the whole stand. Understory removal is the harvest of sub-merchantable trees in the lower stratum of a multi-storied stand. This story usually consists of shade-tolerant conifers with low crowns. Where the understory is well developed its removal may also reduce the effective *CBD* of the stand.

A combination of treatments — such as thinning with broadcast burning — is simulated by adding individual effects. The overall effect of a combination of treatments on a factor where the individual effects are in opposition (such as the effects of thinning with whole-tree harvest on fuel load) must be determined independently.

Some fuel treatments, such as lopping or chipping, reduce surface spread and intensity by increasing fuelbed bulk density. The effect of these treatments on the crown fire hazard indexes is similar to a decrease in fuel load. These treatments are not specifically treated in this analysis.

DISCUSSION AND CONCLUSION

This paper analyzes the sensitivity of two crown fire hazard indexes to their input factors. The indexes are derived from the coupling of existing models of surface and crown fire behavior using Van Wagner's transition criteria. Like all other fire behavior models, the internal consistency of the indexes will be more reliable than their accuracy. That is, a comparison of the **relative** crown fire hazard of alternative stand conditions will be more reliable than an **absolute** assessment of conditions that lead to crown fire activity.

This analysis of the coupled model suggests that crown base height and surface fuel load are the most important factors affecting crown fire initiation. Foliar moisture content has a much weaker effect. Efforts to mitigate crown fire initiation should therefore include treatments that increase *CBH* and reduce surface fuels. Such treatments include prescribed burning, pruning, and thinning from below. The thinning and pruning treatments should be followed by a slash reduction treatment or the effect of slash fuel will offset the effect of increased crown base height.

Susceptibility to active crowning is most strongly affected by crown bulk density and, to a lesser extent, foliar moisture content. Crown bulk density is easily manipulated by thinning. Foliar moisture content is a function of species and season, and cannot be manipulated by forest management except by altering species composition. However, the Rothermel correlation for crown fire spread rate does not take into account the possible effect of *CBD* on spread rate. The true sensitivity of active crowning to *CBD* could be more or less than indicated here, depending on how variation in *CBD* affects spread rate.

Making crown fire hazard assessments requires knowledge of a stand's crown base height and crown bulk density. Some guidance on the determination of these crown fuel characteristics is available (Alexander 1988, Reinhardt and others in prep, Keane and others 1998). Crown bulk density is commonly estimated by summing the estimated crown weights of individual trees and dividing by crown length. Only the crown fuels which can potentially burn in the flaming front should be included — the foliage, fine dead material, and a portion of the branches less than 6mm diameter. Other methods of estimating crown characteristics from stand exam data are currently under development (Reinhardt and others in prep). The natural fuel photo series (Ottmar 1998) may help in setting values for *CBD*, but a photo series specifically for crown fuel characteristics would be very helpful. Unfortunately, there are no simple rules to relate *CBD* to easily measured stand properties like basal area or trees per acre. Further research on crown fuel characteristics is needed.

A forest fuel complex is dynamic. Dead fuel accumulates from annual litterfall, tree mortality, and disturbances such as wind and ice. Dead fuel is reduced by biological decomposition and fire. Live fuels change as trees, shrubs and herbs grow and die. Therefore, crown fire hazard also changes over time. Temporal changes in the forest fuel complex must be simulated separately. The Fire and Fuels Extension to the Forest Vegetation Simulator can be used to simulate temporal changes in a fuel complex, as well as changes that result from fuel treatments.

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