

Modeling Transitions in Shrubland Fire Behavior Using Crown Fire Modeling Techniques¹

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Abstract

Transitions from one type of fire behavior to another cause difficulty in modeling fire behavior in some shrubland fuelbeds. Under different environmental conditions, some shrub fuel complexes may burn benignly in only surface litter, grass, or low shrubs, or more intensely in the taller main shrub canopy as well. With current surface fire modeling methods, simulating fire behavior in these fuels requires *ex ante* knowledge of which fuels will carry the fire so that the appropriate fire behavior fuel model can be selected. A conifer crown fire simulation technique has been adapted to simulate the transition between surface and shrub-canopy fire. Simulations are based on the Rothermel surface spread model; however, the technique can be adapted to other spread models. Two surface fire behavior fuel models are specified—a “low” fuel model representing the grass, low shrub or litter fuels that support relatively benign fire behavior when the fire remains beneath the main canopy, and a “high” fuel model that represents fire behavior in the main shrub canopy. The method also requires an experience-based estimate of the flame length at which the transition to shrub-canopy fire begins. Standard or custom fire behavior fuel models may be used. Interpretation is similar to that for conifer crown fires.

Introduction

Selecting the best standard surface fire behavior fuel model (FBFM; Albini 1976, Anderson 1982) for some fuel complexes can be difficult because one fuel model often does not fit all environmental conditions. For example, Keane and others (1998) made two FBFM spatial data layers for use in FARSITE (Finney 1998). One layer specifies the most appropriate FBFMs for moderate environmental conditions, and another layer specifies a FBFM to use for extreme conditions (e.g., severe drought). There are no objective guidelines for deciding which FBFM data layer to use for a given set of environmental conditions; the user heuristically decides which layer to use based on quality of the fire behavior simulations relative to observation or expectation. In such a simulation system, *ex ante* knowledge of expected fire behavior is needed in order to predict exactly that-expected fire behavior.

These problems are most prevalent in shrub fuel complexes. In some cases, shrub and shrub-like fuelbeds exhibit transitional behavior, gradual or abrupt changes in fire behavior as the nature of the fire-carrying fuel stratum changes from grass and litter to the main shrub canopy, similar to that of conifer crown fires (Scott and Reinhardt 2001). For example, the Storm King fire spread beneath tall oakbrush during a period of moderate environmental conditions, then later crowned through the oakbrush canopy under the influence of a strong wind (Butler and others 1998).

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In the simulation technique presented here, shrubland fuel complexes may include short coniferous vegetation such as pinyon-juniper or conifer plantation. A shrubland fuel complex may exhibit two very different behaviors in response to a changing fire environment (fuel moisture and wind speed), especially in deep fuel complexes (with resulting separation of the shrub canopy and surface litter). One behavior corresponds to spread primarily through the grass and litter beneath the shrub canopy, the other to spread through the canopy itself. Another example is in patchy shrub or shrub-like fuel complex (e.g., pinyon-juniper) that has a horizontal mixture of two very different surface fuels. Under some conditions fire spreads through only the litter or grass layer, while under other conditions fire may spread through the whole fuel complex, resulting in higher spread rate and fireline intensity. Anecdotal observation of fire behavior in those fuel complexes suggests that fuel condition (fuel moisture), slope, and wind speed all play a role in determining whether the main canopy will support fire spread.

An automated method to scale fire behavior predictions between two FBFM selections might improve fire behavior simulations when knowledge of which fuel stratum is carrying the fire is not available. Such a method should be sensitive to site and environmental conditions (slope steepness, wind reduction to mid-flame level, fuel moisture, and windspeed), as well as fuel characteristics (such as FBFM and available shrub canopy bulk density). This paper describes a “stacked” fuel model concept for use with the Rothermel surface fire spread model.

Modifying NEXUS

The NEXUS crown fire hazard assessment system (Scott 1999) is a Microsoft® Excel spreadsheet that simulates the transition between surface fire and crown fire behavior, based on Van Wagner’s (1977) transition criteria. The Southern Utah Fuels Management Demonstration Project identified the need for a similar transition model for shrub-canopy fires as well as conifer crown fires, especially in pinyon-juniper (P-J) fuels. NEXUS has been modified to accommodate shrub-canopy fire simulations and converted to a stand-alone program, called NEXUS 2.

Crown fire simulation

The original NEXUS conifer crown fire simulation method is described in detail in Scott and Reinhardt (2001). Predicted surface fireline intensity is compared with the critical fireline intensity needed for transition to crown fire using Van Wagner’s (1977) transition criterion. If the threshold is not met, then the model predicts surface fire and the final spread rate and intensity are those of the surface fire. If the initiation criterion is met, then Van Wagner’s second criterion, mass-flow rate, is checked to see if it meets the minimum required for sustained active crown fire spread. Mass-flow rate is the product of crown fire spread rate (predicted in NEXUS using Rothermel’s (1991) correlation) and canopy bulk density. If this second criterion is met as well, the model predicts active crowning and final spread rate and intensity are those of the crown fire; if not, the model predicts passive crowning.

The simulations use information about the fire environment to determine which type of fire is likely to occur: surface fire, passive crown fire, or active crown fire. Spread rate and intensity in a passive crown fire are scaled between separate predictions for surface and active crown fire.

Shrub-canopy fire simulation

NEXUS 2 has been modified to simulate shrub-canopy fires as well as conifer crown fires. No predictive model of transition from surface to shrub-canopy fire is available, so the user must input the flame length at which the transition from surface to shrub-canopy fire is expected to take place. Using Byram's (1959) flame length model, NEXUS 2 converts this surface fire flame length to fireline intensity, which is then used in place of Van Wagner's initiation criterion (minimum required fireline intensity). For plotting on a shrub-canopy fire hazard assessment chart (*fig. 1*), fireline intensity is divided by heat per unit area to estimate its equivalent in terms of spread rate. Using Rothermel's model, heat per unit area is a function of FBFM and fuel moisture, but not slope or wind speed.

Van Wagner's mass-flow rate criterion for conifer crown fires is used in modeling shrub-canopy fires as well. The available shrub canopy bulk density must be provided to NEXUS 2. This is a rarely measured variable in the fuel types to which it may be applied, such as pinyon-juniper or oakbrush. Until research provides reliable values for available shrub canopy bulk density, this method must be applied with caution.

The shrub-canopy fire model uses information about the fire environment to determine if fire behavior will be determined by the low or the high fuel model, or if behavior will fall in the transition zone in between.

Shrub-canopy transition indices

In modeling the hazard of conifer crown fires, NEXUS computes two indices of crown fire potential: Torching Index (TI) and Crowning Index (CI). The TI is the 20-ft windspeed at which some kind of crowning is possible; it is the point at which the predicted surface fireline intensity equals the critical value needed for crown fire initiation. The CI is the 20-ft wind speed at which active crown fire is possible; it is the point at which the potential crown fire spread rate equals the critical value needed to produce the minimum mass-flow rate for maintaining solid flame.

The indices have similar meaning and interpretation when computed for shrub-canopy fires. The TI is the 20-ft wind speed at which flame length predicted for the low FBFM equals the transition flame length value entered by the user. The CI is the 20-ft wind speed at which the spread rate predicted for the high FBFM equals that needed to produce the minimum mass-flow rate for maintaining solid flame, a function of the available shrub canopy bulk density.

The CI can be lower than the TI in many circumstances. In those cases, just as for conifer crown fires, there is no transition region—the fire goes from the low FBFM to the high FBFM with an abrupt jump rather than a smooth transition.

Estimating transitional fire behavior

For the cases where $TI < CI$, final fire behavior for the wind speed region between TI and CI is calculated by scaling between the predictions for the low and high FBFMs. The scaling is based on a transition function (TF) similar to Van Wagner's (1977) crown fraction burned, which produces a value between 0 and 1.

$$SPRT_{final} = SPRT_{low} + TF (SPR_{Thigh} - SPRT_{low})$$

When TF is 0, the formula evaluates to $SPRT_{low}$. When TF is 1, the formula evaluates to SPR_{Thigh} . For $TF=0.5$, the formula estimates $SPRT_{final}$ will be half-way between $SPRT_{low}$ and SPR_{Thigh} .

Details of the TF calculation are provided in Scott and Reinhardt (2001 [Appendix A, equation 28]). Briefly, TF is the fractional amount by which the difference between SPRT_{low} (at the given wind speed) and the transition spread rate exceeds the difference between SPRT_{low} (at CI) and the transition spread rate, with bounds between 0 and 1.

Example Simulation

Inputs

The following stylized example illustrates the application of this modeling concept for a pinyon-juniper fuel complex with a significant component of short grass in the areas between the pinyon and juniper plants. When the fire environment is moderate, only the grass burns, and the pinyon-juniper canopy is not involved in fire spread or intensity. The FBFM that best describes fire spread in the grass is model 1 (short grass). However, local knowledge suggests that spread rate will be approximately 75 percent of that predicted by FBFM 1, so we will use a multiplier of 0.75 in NEXUS. Wind reduction factor is 0.2 for these fuels, because the P-J “overstory” blocks the 20- ft wind from reaching the grass fuels.

For this example, available shrub canopy bulk density is set to 0.10 kg m⁻³ (0.0062 lbs ft⁻³), and the transition flame to 2 feet.

Table 1—Inputs for shrub-canopy fire simulation in NEXUS.

	Low FBFM ¹	High FBFM ¹
Fire behavior fuel model (FBFM ¹)	1 (short grass)	4 (chaparral)
Spread rate multiplier ²	0.75	1.00
Fuel load and depth multiplier ³	1.00	0.75
Wind reduction factor ⁴	0.2	0.4

¹See Anderson (1982) for a complete description.

²Affects rate of spread and fireline intensity linearly

³Affects rate of spread linearly, fireline intensity with square of multiplier

⁴Ratio of mid-flame to 20-ft windspeed

When the fire environment is conducive (stronger winds, steeper slopes, drier fuels), the P-J canopy dominates fire spread and intensity. Local experts indicate that spread rate and fireline intensity in the P-J canopy are best modeled with FBFM 4, but only after reducing the load and depth to 75 percent of the original value. (This has the effect of reducing spread rate to 75 percent and fireline intensity to 56 percent [.75²] of the value predicted by the unadjusted FBFM.) The adjusted spread rate is used to determine if the critical mass-flow rate is achieved. Wind reduction factor is 0.4 for the P-J fuels, because they will produce taller flames and have no blocking overstory. Fire environment inputs represent moderately dry conditions (*table 2*).

Table 2—Fire environment inputs for the stylized example.

	Variable
1-hr timelag moisture content (pct)	5
10-hr timelag moisture content (pct)	6
100-hr timelag moisture content (pct)	7
Live woody moisture content (pct)	85
Slope (pct)	0
20-ft wind speed (mph)	0-40

Outputs

The simulation outputs are best displayed on a shrub-canopy fire hazard assessment chart (*fig. 1*). Plotted over a range of 20-ft wind speeds, the low FBFM spread rate predictions cross the transition spread rate (computed from the transition flame length of 2 ft) at a 20-ft wind speed of 11 mph; that is the Torching Index, where the transition toward a full shrub-canopy fire begins. The high FBFM predictions cross the critical spread rate for full shrub-canopy fire at 16 mph; that is the Crowning Index, where the transition to shrub-canopy fire is complete. The region below the TI indicates fire spread in the low fuel model, using the wind reduction factor and multipliers specified for that model. The region above the CI represents fire spread in the high fuel model, using its wind reduction factors and multipliers. The region between the TI and CI represents transitional fire behavior, analogous to passive crowning in conifer crown fires. Spread rate and intensity rise through the transition zone as more of the shrub canopy becomes involved.

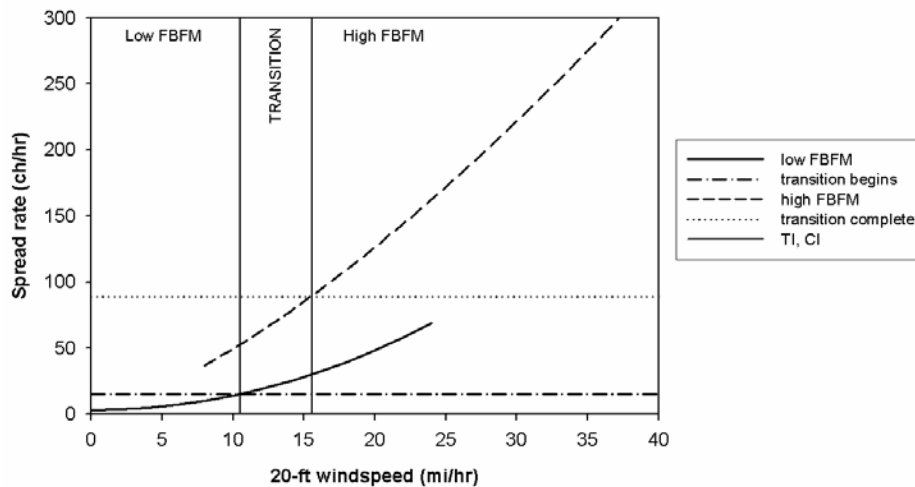


Figure 1—Shrub-canopy fire hazard assessment chart. Lines for low FBFM and transition-begins spread rate cross at the Torching Index, about 11 mi hr⁻¹. The high FBFM spread rate and transition-complete spread rate cross at the Crowning Index, about 16 mi hr⁻¹. Final spread rate follows the low FBFM up to the TI, then bridges the gap between models in the transition region, and finally follows the high FBFM above the CI (*fig. 2*). The steepness of the transition from the low to high FBFM depends on how close are TI and CI; if TI is greater than CI, the change is instantaneous.

Final flame length exhibits similar behavior, but the flame-length gap is larger than the spread-rate gap, so the impact of transition is more severe. Above the CI, final flame length exceeds high FBFM flame length by a small amount; this is because the final flame length is computed from the combined low and high FBFM heat per unit area values rather than just the high.

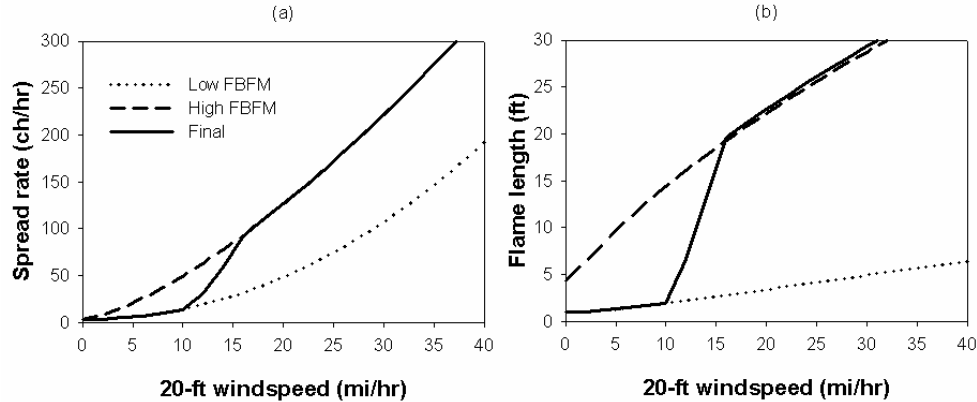


Figure 2—Simulation results for spread rate (a) and flame length (b).

Discussion

The modeling process for simulating shrub-canopy fires in NEXUS 2 appears similar to the two-fuel-model concept of BEHAVE (Andrews 1986) and BehavePlus2 (www.fire.org), but there are important distinctions. The two-fuel-model concept simulates spread rate through a horizontally arranged matrix of two fuel models; overall spread rate is a function of the relative coverage of each fuel model and their respective spread rates. In BEHAVE for DOS there was only one calculation method: area-weighting. In BehavePlus2 there are three methods to choose from: area-weighting, harmonic mean (Fujioka 1985, Martin 1988), and two-dimensional expected spread (Finney 2003). By contrast, NEXUS 2 uses two fuel models in a vertical, or “stacked”, arrangement. The low and high fuel models apply to the same area. The calculation predicts whether predictions for the low or the high fuel model will prevail, for the given set of environmental conditions, and scales the output between them if necessary.

Not all shrubland fuelbeds are appropriate for this simulation method. Shrub fuel complexes in which fire is carried by only one type of fuel (e.g., uniform, low sagebrush) can be adequately modeled with current methods using only one FBFM. The stacked fuel model simulation technique is suited for shrub (and shrub-like) fuel complexes, typically modeled with Rothermel’s surface fire spread model, that exhibit a such a degree of fuel separation that two distinct behavior responses may occur. For example, pinyon-juniper and tall oakbrush or chaparral fuel complexes are appropriate for consideration.

Sufficient fire behavior observation data do not exist to validate (or invalidate) this modeling approach. The availability of this modeling method may encourage the collection of data to test its validity.

The stacked fuel model concept can be used with standard or custom surface fire behavior fuel models. The only limitation is that the simulations must predict higher spread rate for the high FBFM than the low under all wind and fuel moisture

conditions. A new set of standard FBFMs has been developed³. The stacked fuel model concept will work with those models as well.

While this paper describes fuel model stacking to model transitions in shrubland fire behavior, the concept is equally applicable to other fuel types. For example, in forested fuel complexes the surface litter often carries the fire under moderate environmental conditions while under more extreme conditions the fire may be carried by combined litter and shrub fuels. This can be simulated by specifying a low FBFM for the moderate conditions (e.g., FBFM 8, compact timber litter), a high FBFM for the more extreme conditions (e.g., FBFM 10, timber litter and understory), and the flame length at which the transition begins.

The stand-alone version of NEXUS capable of making these stacked shrub-canopy fire simulations will be available for beta testing in fall 2004. Visit www.fire.org/nexus/nexus.html for more information and to download the program when available.

Conclusions

Transitions in fire behavior similar to crown fires occur in many shrub fuel complexes. Standard fire behavior fuel models and modeling systems do not simulate such transitions; custom models can be built to approximate such abrupt changes, but usually with poor results.

NEXUS 2 has been modified to simulate shrubland fire behavior as a transition between two selected fire behavior fuel models.

Interpretation of the transition is similar to that for conifer crown fires. The Torching Index is the 20-ft windspeed at which transition from the low to the high FBFM begins, given the site and fire environment variables. The Crowning Index is the 20-ft wind speed at which the transition to the high FBFM is complete. The relative steepness of the transition from the low to high FBFM depends on the separation of TI and CI. When CI is less than TI the transition is instantaneous, and a hysteresis exists (Scott and Reinhardt 2001).

This method relies heavily on user-provided inputs that are not well known or easy to estimate. To be useful, we need data on canopy bulk density of fuel complexes like pinyon-juniper, a model of transition for shrub fuel complexes, and validation data.

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³Scott, J. H. and Burgan, R. E. 2004. A new set of standard fire behavior fuel models for use with Rothermel's surface fire spread model. Final Report on file at the Missoula Fire Sciences Lab, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; Missoula, Montana (electronic document).

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