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Comparison of Crown Fire Modeling Systems Used in Three Fire Management Applications

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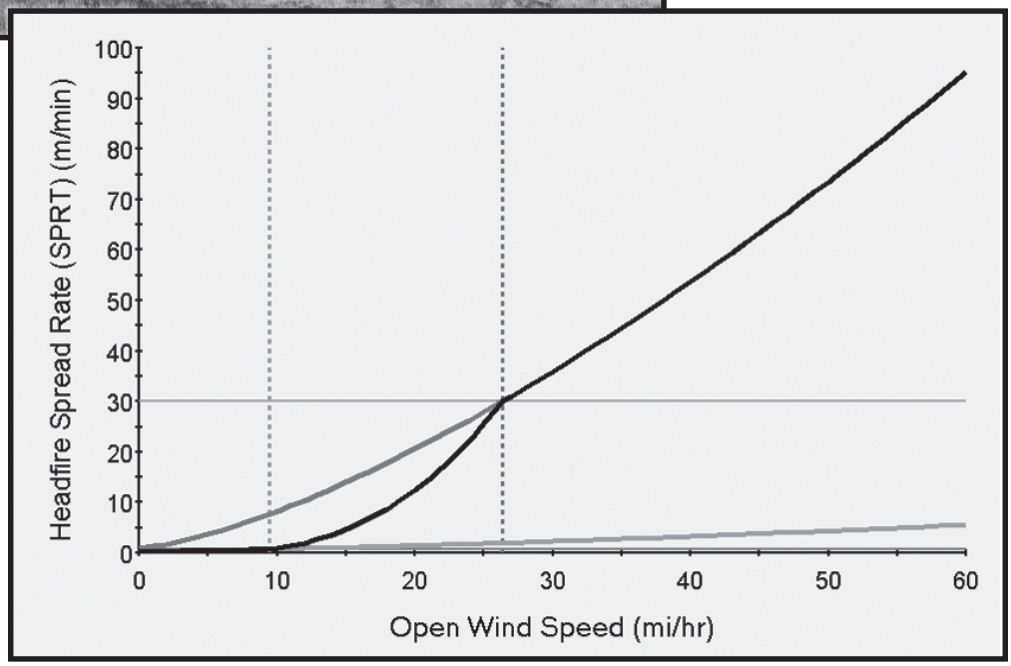

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Abstract

The relative behavior of surface-crown fire spread rate modeling systems used in three fire management applications—CFIS (Crown Fire Initiation and Spread), FlamMap and NEXUS—is compared using fire environment characteristics derived from a dataset of destructively measured canopy fuel and associated stand characteristics. Although the surface-crown modeling systems predict the same basic fire behavior characteristics (type of fire, spread rate) using the same basic fire environment characteristics, their results differ considerably. Across the range of inputs used in these comparisons, CFIS predicted the highest incidence of crown fire and the highest resulting spread rates, whereas FlamMap predicted the lowest crown fire incidence and lowest spread rates. NEXUS predictions fell between those two systems.

Keywords: forest fire behavior modeling, transition, crown fraction burned, rate of spread, FlamMap, NEXUS, CFIS

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Comparison of Crown Fire Modeling Systems Used in Three Fire Management Applications

Joe H. Scott

Introduction

Early efforts to predict wildland fire behavior characteristics were focused on surface fires, primarily their rate of spread and intensity. Later research and development efforts have produced several physics-based research models (Albini 1996, Butler and others 2004, Grishin 1997, Linn and others 2002) and operational models (Cruz and others 2004, 2005, Forestry Canada Fire Danger Group 1992, Rothermel 1991) for predicting crown fire occurrence and spread rate. The physics-based models, based on principles of combustion chemistry, fluid dynamics, and heat transfer, are calculation intensive and costly to operate, precluding their application to most fire management problems. However, physics-based models could be used to study a variety of wildland fire phenomena (Linn and others 2002), including fire-atmosphere interactions, plume domination, ember transport, steady-state spread, and initiation and cessation of crown fire. Operational models of crown fire spread rate, based largely on empirical data collected on both unplanned and experimental fires, are simple mathematical models whose great speed of calculation and relative ease of use allows application to important fire management problems at large spatial and temporal scales (for example, assessing fire potential across a large landscape, or predicting large fire growth over many days). Unlike the physics-based models, which enjoy broader applicability, valid use of empirical models is restricted to situations similar to those on which the models were built.

For purposes of this paper, a *fire model* is defined as a mathematical relationship that describes a single aspect of a fire (Andrews and Queen 2001). Rothermel's (1972) model for predicting flame front spread rate at the head of a surface fire is a notable example. A *fire modeling system* is a series of fire models used in concert to predict another aspect of fire. For example, separate models of surface fireline intensity and minimum fireline intensity crown fire initiation are used together to predict whether a crown fire can initiate (Alexander 1988, Van Wagner 1977). A *fire management application* is one or more models or systems applied coherently to support fire management decisionmaking. FARSITE, for example, is a fire management application incorporating dozens of models and modeling systems to simulate fire growth across a two-dimensional landscape; its output is used to support decisions regarding appropriate response on wildfires and wildland fire use incidents.

A variety of surface-crown spread rate modeling systems have been incorporated into fire management applications over the past decades, including BehavePlus version 3 (Andrews and others 2005), the Canadian Forest Fire Behavior Prediction System (CFFBPS; Forestry Canada Fire Danger Group 1992), FARSITE (Finney 1998), FlamMap (Finney and others 2006), FFE-FVS (Reinhardt and Crookston 2003), FMAplus (Carlton 2005), NEXUS (Scott 1999, Scott and Reinhardt 2001), and

CFIS (Crown Fire Initiation and Spread; Cruz and others 2005). The surface-crown spread rate system in each of those applications integrates separate models of surface fire behavior characteristics (intensity or fuel consumption), transition to crown fire (or crown fire occurrence), and crown fire spread rate. Of the eight systems identified above, six (all but CFIS and CFFBPS) are built upon a common set of component fire models that includes Rothermel's (1972) surface fire spread rate and (1991) crown fire spread rate models, and Van Wagner's (1977) crown fire initiation and spread models. Of those six systems, FlamMap and FARSITE employ identical surface-crown spread rate systems. FlamMap 3.0 and FARSITE 4.1.05 now include a switch that enables the user to select between their standard method (Finney 1998) and a new method based largely on NEXUS (Scott and Reinhardt 2001). The FlamMap and FARSITE implementation of Scott and Reinhardt (2001) does not include condition crown fire, but in all other respects is identical to the results of NEXUS. This paper will help a user interpret the impact of that switch on fire behavior simulations. The surface-crown systems in FFE-FVS and BehavePlus are consistent with that of NEXUS. FMAplus can be set, at the user's discretion, to use the surface-crown system of either FARSITE/FlamMap or NEXUS. Therefore, detailed comparison of the surface-crown spread rate systems in FlamMap, NEXUS, CFIS, and CFFBPS covers the range of surface-crown spread rate systems used in current fire management applications. For most fuel types, the CFFBPS integrates surface and crown fire spread rates into a single predictive equation that encompasses the full range of behavior, whether surface or crown. However, for fuel type C-6 (conifer plantation), separate equations are used for surface and crown fire behavior, and a transition function is used to scale between the separate predictions – the first implementation of such a dual-equation approach in an operational system. However, due to fundamental differences in inputs between the CFFBPS and the others, I do not include the CFFBPS in the detailed comparisons.

The purpose of this paper is to compare the primary outputs of the surface-crown spread rate systems used in CFIS, FlamMap, and NEXUS. The descriptions and comparisons presented in this paper will be useful for interpreting output from those fire management applications.

Study Areas

Rather than exercise each system through the entire range of possible input values, as in a sensitivity analysis, I made the comparisons for five intensively sampled conifer stands for which stereo photographs, stand data, and canopy fuel characteristics were readily available (Scott and Reinhardt 2005):

- ponderosa pine/Douglas-fir (PPDF)
- pure ponderosa pine (PP)
- Douglas-fir (DF)
- lodgepole pine (LP)
- Sierra Nevada mixed conifer (SNMC).

The multi-storied PPDF stand is located on a gentle NE-facing slope west of Missoula, Montana. The ponderosa pine overstory is approximately 120 years old. Douglas-fir has established in the under- and middle-story, creating continuous canopy fuel from the ground to the top of the canopy. The single-storied PP stand is located on a gentle slope near Flagstaff, Arizona. Ponderosa pine is both the existing and potential natural vegetation type, even without fire; no other conifer species are present in this forest. The plot was established in the densest part of a dense stand, thus the high initial basal area (BA = 69.0 $m^2\ ha^{-1}$; table 1). The single-storied DF stand is located on a moderately steep southeast-facing slope southwest of Salmon, Idaho. Douglas-fir dominates the plot, with

Table 1—Stand and fuel characteristics of five conifer stands. Site and stand characteristics are from Scott and Reinhardt (2002). Canopy fuel characteristics are from Scott and Reinhardt (2005). Surface fuel and miscellaneous characteristics are assumed or calculated from other inputs.

	PPDF	PP	DF	LP	SNMC
		Site characteristics			
Slope (pct)	6	11	25	7	7
Aspect	NNE	S	SE	NE	NNE
Elevation (m)	1050	2308	2300	2290	1300
		Stand characteristics			
SD (# ha^{-1})	481	2070	1178	1146	382
BA (m2 ha^{-1})	30.4	69.0	36.3	42.7	46.8
SH (m)	23	16	17	20	34
CC (pct)	59	69	70	52	74
		Canopy fuel characteristics			
CBD (kg m^{-3})	0.089	0.166	0.257	0.112	0.101
CBH (m)	0	5	1	1	2
CFL (kg m^{-2})	1.40	0.93	2.09	1.00	1.72
FMC (pct)	100	100	100	100	100
		Surface fuel characteristics			
FBFM	10	10	10	10	10
EFFM (pct)	6	6	6	6	6
LFM (pct)	80	80	80	80	80
SFC (kg m^{-2})	1.5	1.5	1.5	1.5	1.5
		Miscellaneous			
WAF (fraction)	0.10	0.11	0.10	0.10	0.10

Notes: *SD* = stem density (greater than 10 cm d.b.h.), *BA* = basal area, *SH* = stand height, *CC* = canopy cover, *CBD* = canopy bulk density, *CBH* = canopy base height, *CFL* = canopy fuel load, *FMC* = foliar moisture content, *FBFM* = fire behavior fuel model, *EFFM* = estimated fine dead fuel moisture, *LFM* = live fuel moisture, *SFC* = surface fuel consumption, and *WAF* = wind adjustment factor.

a small amount of lodgepole pine. The single-storied LP stand is located on a gentle slope east of Helena, Montana. A shade-tolerant understory of subalpine fir was only beginning to establish in this stand. The SNMC stand (composed of white fir, incense cedar, ponderosa pine, and Douglas-fir) is located at Blodgett Forest Research Station, SE of Auburn, California. This stand originated after clearcut logging around 1910, and was treated with commercial thinning about 20 years prior to sampling. Despite the origin and management of this stand, its canopy fuel profile is more similar to a multi-storied stand than single-storied, due in part to the high productivity of the site and presence of shade tolerant species. Scott and Reinhardt (2002, 2005) describe these five stands and their associated canopy fuel characteristics in more detail.

I also compared system outputs for the PPDF stand at various levels of residual basal area (*BA*) resulting from low thinning (Scott and Reinhardt 2005). The first level, understory removal (UR), simulates removal of all trees less than 5 cm d.b.h. Subsequent levels simulated progressive removal, from below (smallest diameter trees first), of 25, 50, and 75 percent of the initial *BA*.

Fire Environment

Measured, estimated, or assumed fire environment characteristics (fuel, weather, and topography) are described below and summarized for each stand (table 1), and for the PPDF stand across different levels of simulated canopy fuel reduction treatment (table 2).

Table 2—Stand and fuel characteristics of a ponderosa pine-Douglas-fir stand through progressive levels of basal area (BA) removal. Site and stand characteristics are from Scott and Reinhardt (2002). Canopy fuel characteristics are from Scott and Reinhardt (2005). Surface fuel and miscellaneous characteristics are assumed or calculated from other inputs

	Initial stand	Understory removed	25% Basal area removed	50 % Basal area removed	75% Basal area removed
			Site characteristics		
Slope (pct)	6	6	6	6	6
Aspect	NNE	NNE	NNE	NNE	NNE
Elevation (m)	1050	1050	1050	1050	1050
			Stand characteristics		
SD (# ha^{-1})	481	481	226	113	57
BA (m2 ha^{-1})	30.4	30.0	23.3	16.6	9.2
SH (m)	23	23	23	23	23
CC (pct)	59	59	50	30	19
			Canopy fuel characteristics		
CBD (kg m^{-3})	0.089	0.086	0.055	0.037	0.022
CBH (m)	0	1	5	11	12
CFL (kg m^{-2})	1.40	1.33	0.76	0.40	0.24
FMC (pct)	100	100	100	100	100
			Surface fuel characteristics		
FBFM	10	10	10	10	10
EFFM (pct)	6	6	5	4	3
LFM (pct)	80	80	80	80	80
SFC (kg m^{-2})	1.5	1.5	1.5	1.5	1.5
			Miscellaneous		
WAF (fraction)	0.10	0.10	0.11	0.18	0.22

Notes: *SD* = stem density (greater than 10 cm d.b.h.), *BA* = basal area, *SH* = stand height, *CC* = canopy cover, *CBD* = canopy bulk density, *CBH* = canopy base height, *CFL* = canopy fuel load, *FMC* = foliar moisture content, *FBFM* = fire behavior fuel model, *EFFM* = estimated fine dead fuel moisture, *LFM* = live fuel moisture, *SFC* = surface fuel consumption, and *WAF* = wind adjustment factor.

Fuel—Canopy fuel characteristics for each stand were taken directly from Scott and Reinhardt (2005). Canopy bulk density (*CBD*) was defined as the maximum 3-m vertical running mean bulk density of available canopy fuel, which includes the foliage, 0-3 mm live branchwood, and 0-6 mm dead branchwood. *CBD* varies from a low of 0.089 kg m^{-3} in the PPDF stand to 0.257 kg m^{-3} in the DF stand (table 1). In the PPDF stand, *CBD* decreased to 0.022 kg m^{-3} after removal of 75 percent of the initial basal area (table 2). Canopy base height (*CBH*) is defined as the lowest height above the ground at which the canopy bulk density exceeds a threshold of 0.011 kg m^{-3}. Using this criterion, initial *CBH* varies from 0 m in the PPDF stand to 5 m in the PP stand (table 1). In the PPDF stand, *CBH* increased to 12 m after removal of 75 percent of the initial *BA* (table 2). Foliar moisture content (*FMC*) is assumed to be 100 percent for all species at all sites (Philpot and Mutch 1971). (Table 3 contains a complete list of variables used in this paper.)

To focus the analysis on the relative behavior of the models and systems (as opposed to the stands themselves), I assumed that surface fuels in each of the stands are represented by fire behavior fuel model 10 (FBFM 10; Albini 1976, Anderson 1982). Further, I assumed that FBFM 10 would still represent surface fuels after each level of canopy fuel reduction in the PPDF stand.

Fine dead surface fuel moisture (*EFFM*) was estimated using Rothermel's (1983) fuel moisture tables, assuming a late summer, mid-afternoon fire, using the same general weather condition (temperature and humidity) for all simulations. The tables indicated

Table 3—Complete list of variables.

CBD	canopy bulk density (kg m^{-3})
CBH	canopy base height (m)
CD	canopy depth (m)
CFB	crown fraction burned (dimensionless)
CFL	canopy fuel load (kg m^{-2})
EFFM	estimated fine (dead) fuel moisture content (percent)
FBFM	fire behavior fuel model (categorical)
FMC	foliar moisture content (percent)
FSG	fuel strata gap (m)
I	fireline intensity (kW m^{-1})
I'_s	critical surface fireline intensity to initiate crown fire (kW m^{-1})
R	rate of spread (m min^{-1})
R_a	rate of spread of an active crown fire (m min^{-1})
$R_{a(max)}$	near-maximum rate of spread of an active crown fire (m min^{-1})
R_{final}	final fire rate of spread, whether surface or crown (m min^{-1})
R'_a	critical crown fire rate of spread to sustain active crown fire (m min^{-1})
R_p	passive crown fire rate of spread (m min^{-1})
R_s	surface fire rate of spread (m min^{-1})
R'_s	critical surface fire rate of spread to initiate crown fire (m min^{-1})
R'_{sa}	surface fire rate of spread for U_{10} = CI (m min^{-1})
S	mass flow rate (kg m^{-2} min^{-1})
SFC	surface fuel consumption (kg m^{-2})
U_{10}	wind speed 10 m above the surrounding vegetation (km hr^{-1})
WAF	wind adjustment factor (dimensionless)

an *EFFM* of 6 percent for the initial condition for all stands (table 1). In the PPDF stand, *EFFM* was estimated to be 3 percent after removal of 75 percent of initial basal area (table 2). Canopy cover remained unchanged after removal of the understory; therefore the initial condition and UR treatment were given the same *EFFM* value of 6 percent. The two intermediate levels of treatment were assigned *EFFM* of 4 and 5 percent so that *EFFM* decreased evenly with treatment (table 2). For use in Rothermel's surface fire spread model, 10-hr timelag moisture content was assumed to be 1 percentage point higher than *EFFM*; 100-hr timelag moisture content was assumed to be 2 percentage points higher than *EFFM* (Rothermel 1983). Live surface fuel moisture content was assumed to be 80 percent, representing dry, late summer conditions.

An estimate of surface fuel consumption (*SFC*) is required for the Cruz and others (2004) crown fire occurrence model, which classifies *SFC* into three categories. Because I do not have estimates of surface fuel load to use for estimating *SFC*, I simply assigned *SFC* to the middle category (1 – 2 kg m^{-2}) for all stands and all levels of *BA* removal.

Weather—I assumed an afternoon temperature of 21–32 °C and relative humidity of 15–19 percent for all stands and levels of *BA* removal. Wind speeds above and below the forest canopy are important variables in the models and systems being compared. Rather than assume a single wind speed for the comparisons, I computed system outputs over a range of open wind speeds (U_{10}; wind speed measured 10 m above the forest canopy), and the U_{10} at which the systems predict a certain type of crown fire would occur.

Mid-flame wind speed is a required input for predicting surface fire spread rate in Rothermel's (1972) model. I estimated mid-flame wind speed by multiplying U_{10} by a wind adjustment factor (*WAF*), which is the ratio of open to mid-flame wind speed. *WAF* was estimated using Albini and Baughman's (1979) model for forested areas on flat ground, with a lower limit of 0.10. Unconstrained, the Albini and Baughman (1979) model indicates *WAF* = 0.09 for the DF stand and 0.08 for the SNMC stand. Their model

computes *WAF* assuming open wind speed is measured at 6.1 m rather than 10 m. U_{10} was converted to $U_{6.1}$ by dividing by 1.15 (Turner and Lawson 1978). *WAF* varied from 0.10 to 0.11 for the initial condition of all stands (table 1), which is consistent with the Rothermel (1983) guideline for dense canopies on flat ground. For the PPDF stand, *WAF* increased from a minimum of 0.10 for the initial condition (table 1) to 0.22 for the most open treatment level (table 2). Wind direction was assumed to be upslope in all cases.

Topography—Slope steepness at each site was gentle; only the DF site exceeded 11 percent slope (table 1).

Background: Component Models

It is helpful to first review the relative behavior of the component models that comprise each spread rate modeling system before comparing them.

Crown Fire Spread Rate

Following significant crown fire events of the 1988 fire season, Rothermel (1991) constructed a simple statistical model of the behavior of sustained crown fire runs in the northern Rocky Mountains. The dataset consisted of eight crown fire runs on seven documented wildfires. Duration of crown fire runs varied from 45 minutes to several hours. Observed average crown fire spread rate was estimated as the total distance of the run divided by its duration. In addition to this average spread rate for the run, Rothermel also estimated the maximum crown fire spread rate observed during the run (these data were available for only five of the eight runs). Slope steepness, open (6.1-m) wind speed, and dead and live surface fuel moistures were estimated for each run. The observed average crown spread rate was correlated linearly with predictions made with the Rothermel (1972) surface fire spread model as adjusted by Albini (1976), using FBFM 10 (Albini 1976, Anderson 1982). FBFM 10 was used for the correlation in all cases, even though a different FBFM might have better represented actual surface fuels. Wind speeds at 6.1 m were adjusted by a factor of 0.4 to estimate mid-flame wind speed (even though a different wind adjustment factor might have been chosen for actual conditions) because it better represented "mid-flame" wind speed of an active crown fire. In Rothermel's correlation, average crown fire spread rate is 3.34 times faster than the predictions made with FBFM 10 using a 0.4 wind adjustment factor.

$$R_a = 3.34 * R_{s(FBFM=10;WAF=0.4)} \tag{1}$$

Where $R_{s(FBFM=10;\,WAF=0.4)}$ is the surface fire spread rate predicted with FBFM 10 using a 0.4 wind adjustment factor. Near-maximum spread rate is 1.7 times faster than the average spread rate.

$$R_{a(max)} = 1.7 R_a \tag{2}$$

During crown fire runs of those durations, medium- or long-distance spotting could have contributed to overall fire growth and, therefore, to its estimated spread rate. However, there is no way to determine the magnitude of the spotting effect on spread rate, if any, on any of the fires in Rothermel's analysis. In that respect, compared to crown fire spread rate models developed without spotting (that is, for shorter durations or on smaller fires, such as experimental crown fires), Rothermel's model might over-predict spread rate. On the long runs used in the correlation, which covered many thousands of acres each, canopy and surface fuels, topography, and wind speed likely varied considerably. The fires may have experienced lulls, periods of surface spread, or only passive crowning at times during the run, potentially leading to under-prediction of fully active crown fire spread rate. Rothermel's near-maximum spread

rate model, based on shorter, higher spread rate runs, would be less affected by temporal and spatial variability in the fire environment.

Rothermel's average and near-maximum crown fire spread rate models predict little variation in spread rate among sites (fig. 1a). The only input that varied among sites was slope steepness, so variation in that input accounted for all of the variation in predicted output. The DF stand is predicted to have slightly higher spread rate than the others due to its steeper slope. In the PPDF stand, predicted spread rate increased as the canopy was opened (BA removed) due to treatment (fig. 1b), because surface fuel moisture was predicted to decrease.

Using a database of 25 active crown fires, Cruz and others (2005) constructed a non-linear regression model to predict active crown fire spread rate from U_{10}, *EFFM*, and *CBD*. Data for the regression consisted of small-scale experimental crown fires (small-scale only in relation to the typical size of a naturally occurring crown fire) in mature and immature jack pine (*Pinus banksiana*), black spruce (*Picea mariana),* and red pine (*Pinus resinosa*) plantations. A fire was considered an active crown fire if its spread rate was at least 90 percent of that needed to maintain a mass flow rate of 3.0 kg m^{-2} min^{-1} (0.05 kg m^{-2} s^{-1}) for the observed *CBD* (Van Wagner 1977). Predicted active crown fire spread rate is

$$R_a = 11.02 * U_{10}^{0.9} * CBD^{0.19} * e^{(-0.17 EFFM)} \tag{3}$$

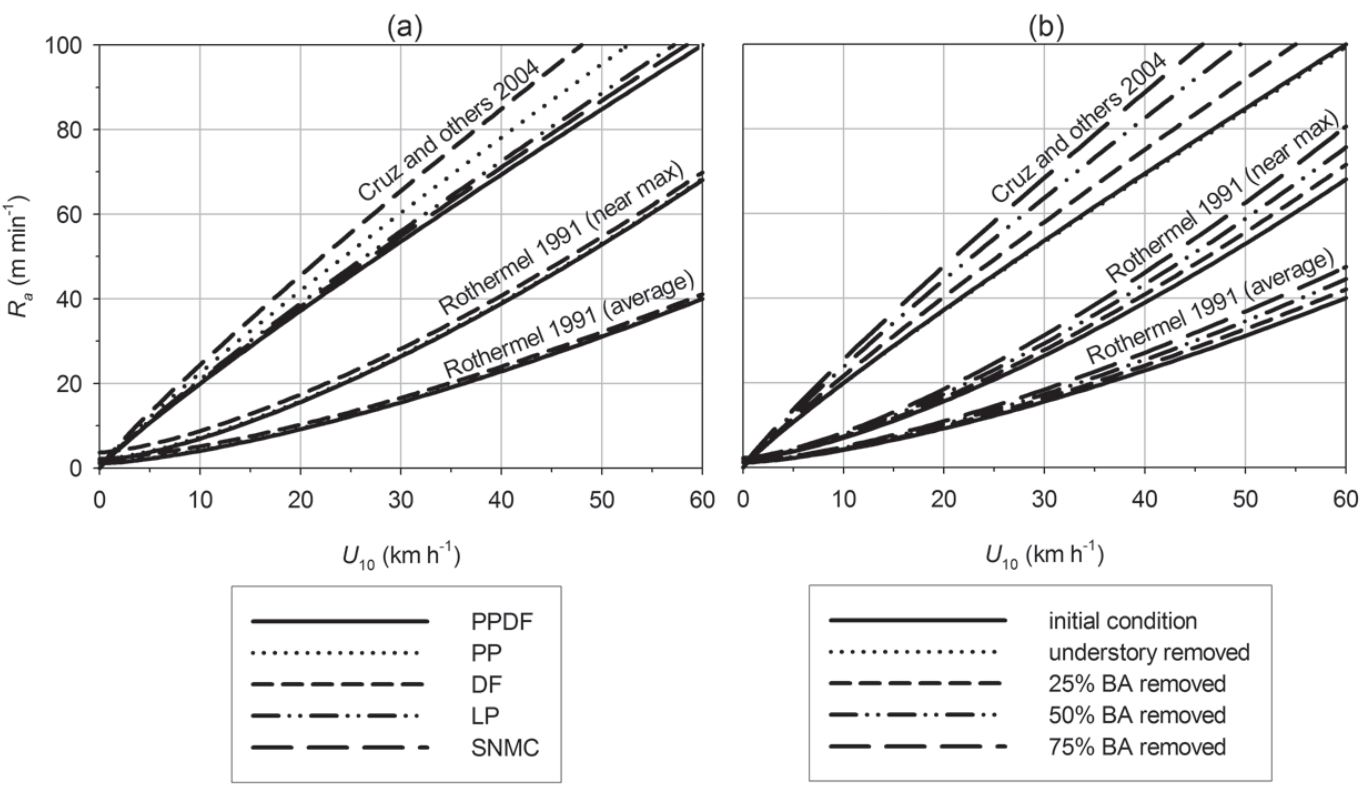

Figure 1—Potential active crown fire rate of spread (R_a) as predicted by three different models for a range of open wind speeds (U_{10}) in (a) five different conifer stands, and (b) a ponderosa pine/Douglas-fir stand as basal area (BA) is removed to simulate low thinning. Complete model inputs are described in tables 1 and 2. Forest types include: PPDF = ponderosa pine/Douglas-fir; PP = ponderosa pine; DF = Douglas-fir; LP = lodgepole pine; and SNMC = Sierra Nevada mixed-conifer.

The Cruz and others (2005) spread rate model does not include slope as a predictive factor; most of the fires used in the regression were on essentially flat ground (< 11 percent slope).

Because *EFFM* was the same for the initial condition of all sites, variation in predicted active crown fire spread rate with the Cruz and others (2005) model is due entirely to variation in *CBD*; the DF stand has the highest predicted spread rates because it has the highest *CBD* (fig. 1a). As the PPDF canopy was opened, *EFFM* and *CBD* both decreased. Those variables have opposing effects on spread rate in the Cruz and others (????) model, decreasing *CBD* leads to lower spread rate while decreasing *EFFM* leads to higher spread rate. Potential crown fire spread rate was predicted to increase as the canopy is progressively opened (fig. 1b) because the effect of *EFFM* overpowered that of *CBD*.

In summary, the two Rothermel (1991) models and the Cruz and others (2005) crown fire spread rate model predicted the initial condition of the DF stand would have the highest R_a of the five sites, but for different reasons; Rothermel's for that stand's relatively steep slope, and Cruz and others for its relatively high *CBD*. There is no overlap in predictions using the three models across the stands or simulated treatments. Predicted R_a is primarily determined by model choice rather than by the range of inputs for the example stands (fig. 1). Rothermel's near-maximum spread rate model predicts (by design) spread rate values 1.7 times the average. Over the range of U_{10} between 10 and 60 km h^{-1}, the Cruz and others model predicts crown fire spread rate between 2.5 and 5.1 times the Rothermel average, and between 1.1 and 3.0 times the Rothermel near-maximum. This variation in predicted spread rates is presumably due to differences in nature of the fires used for constructing each model. Rothermel's crown fires were long-duration runs in coniferous forests of the western United States. Even the near-maximum spread rates he used were of much longer duration than the observations used by Cruz and others, and could have included periods of passive crown fire or surface fire spread. By contrast, the fires used in the Cruz and others model were much shorter duration experimental crown fires primarily in the northern forests of Canada. The experimental crown fires were small compared to the usual size of a crown fire. In most cases, the linear dimensions of the experimental plots were only three to five times the flame length. A large free-burning crown fire might have a much different response to environmental conditions than a small experimental crown fire.

The Rothermel models do not include *CBD* as a predictive factor, whereas *CBD* has a small, directly proportional effect on R_a in the Cruz and others model. By contrast, Grishin (1997) found that increasing *CBD* would lead to a decrease in R_a, due to the higher energy requirement to heat the additional fuel. Albini's (1996) radiation-driven crown fire spread rate model predicts R_a inversely proportional to *CBD* for small *CBD* values, then directly proportional for higher values (Butler and others 2004).

Crown Fire Occurrence or Initiation

In this section I review the operational aspects of a model of crown fire initiation (Van Wagner 1977) and one of crown fire occurrence (Cruz and others 2004). Detailed review of the history and development of models to predict the transition to crown fire can be found elsewhere (Alexander 1998, Cruz 1999, Cruz and others 2004). The distinction between crown fire initiation and occurrence may be important when interpreting model and system output. Crown fire initiation is the onset of crowning; a crown fire initiation model predicts whether a surface fire will transition to some kind of crown fire for a given fire environment. Crown fire occurrence is the observation of some kind of crown fire (for example, passive or active). A crown fire occurrence model predicts whether some kind of crown fire will be observed for a given fire environment. The distinction can be important in cases where a crown fire cannot initiate (due to high

CBH or low fireline intensity, for example) but an active crown fire can still occur if initiated elsewhere (due to high *CBD* or strong wind). If such a conditional crown fire is possible (Scott and Reinhardt 2001), crown fire may occur where it cannot initiate. The possibility of conditional crown fire is important for both wild and experimental crown fires. For example, the purpose of the International Crown Fire Modeling Experiment (ICFME; Stocks and others 2004) was to observe and measure active crown fire characteristics, so a TerraTorch was used to ignite a crown fire rather than see if one would ignite further into the experimental plot. There is no guarantee that a crown fire could have initiated on its own under the same conditions. If a similar situation existed for the experimental fires comprising a crown fire occurrence database, then over-prediction of the onset of crowning relative to a crown fire initiation model is possible.

Van Wagner (1977) theorized that canopy fuels would ignite when the heat supplied by a surface fire drives off their moisture and raises them to ignition temperature. Using a single observation of crown fire initiation in a jack pine stand to estimate an empirical constant, Van Wagner identified the minimum surface fireline intensity required to ignite canopy fuels, I'_s (kW m^{-1}), as a function of height of canopy fuels above the ground (*CBH*) and foliar moisture content (*FMC*).

$$I'_s = \left(\frac{CBH(460 + 25.9FMC}{100} \right)^{3/2} \tag{4}$$

Because *FMC* is held constant for all cases, variation in I'_s results solely from variation in *CBH*, the variable to which the model is most sensitive (Alexander 1988, Scott 1998). Using Van Wagner's (1977) model, $I'_s = 0$ kW m^{-1} in the initial PPDF stand (eq. 4) because $CBH = 0$ (table 4). I'_s increased as BA was removed from the PPDF stand (table 4) because *CBH* increased.

Van Wagner's transition model alone does not provide enough information to determine if transition occurs—an estimate of I_s for comparison with I'_s is also required. To more directly compare the results of Van Wagner's model with those of Cruz and others, I computed I_s with Rothermel's surface fire spread model. For more direct comparison with the Cruz and others (2004) crown fire occurrence model (see below),

Table 4—Critical fireline intensity (I'_s; kW m^{-1}) as calculated with Van Wagner's (1977) crown fire initiation model for the initial condition of five conifer stands and for a ponderosa pine/Douglas-fir stand through several levels of basal area (BA) removal.

Five stands, initial condition	
PPDF	0.0
PP	1883
DF	168
LP	168
SNMC	476
PPDF stand	
Initial condition	0.0
Understory removed	168
25% BA removed	1883
50% BA removed	6145
75% BA removed	7002

I compute the transition ratio (I_s/I'_s), the ratio of predicted surface fireline intensity to the critical fireline intensity needed to initiate a crown fire (Andrews and others 2004). A crown fire is predicted to initiate if $I_s/I'_s \geq 1$.

In the PPDF initial condition, the transition ratio (Andrews and others 2004), I_s/I'_s, was infinity and crown fire initiation is therefore expected at all combinations of U_{10} and *EFFM*. Initiation of crown fire was also predicted to occur easily in the DF stand due to the combination of relatively steep slope and low *CBH*, and was most difficult in the PP stand due to the relatively high *CBH* (fig. 2a). After removing the PPDF understory, *CBH* increased but canopy cover (and therefore *WAF*) remained the same, so crown fire would now initiate only if U_{10} is greater than about 18 km h^{-1} (fig. 2b). After only 25 percent of the BA had been removed, *CBH* was raised to 5 m, and crown fire would not be expected to initiate even as U_{10} reached 60 km h^{-1} (fig. 2b). The last treatment level, which left only 25 percent of the initial BA, showed an *increase* in the ease with which crown fire would initiate compared to the 50 percent basal area level. This is because the *CBH* did not change much between the two levels (11 m to 12 m), but the *EFFM* decreased and *WAF* increased (table 2), resulting in higher surface fire intensity.

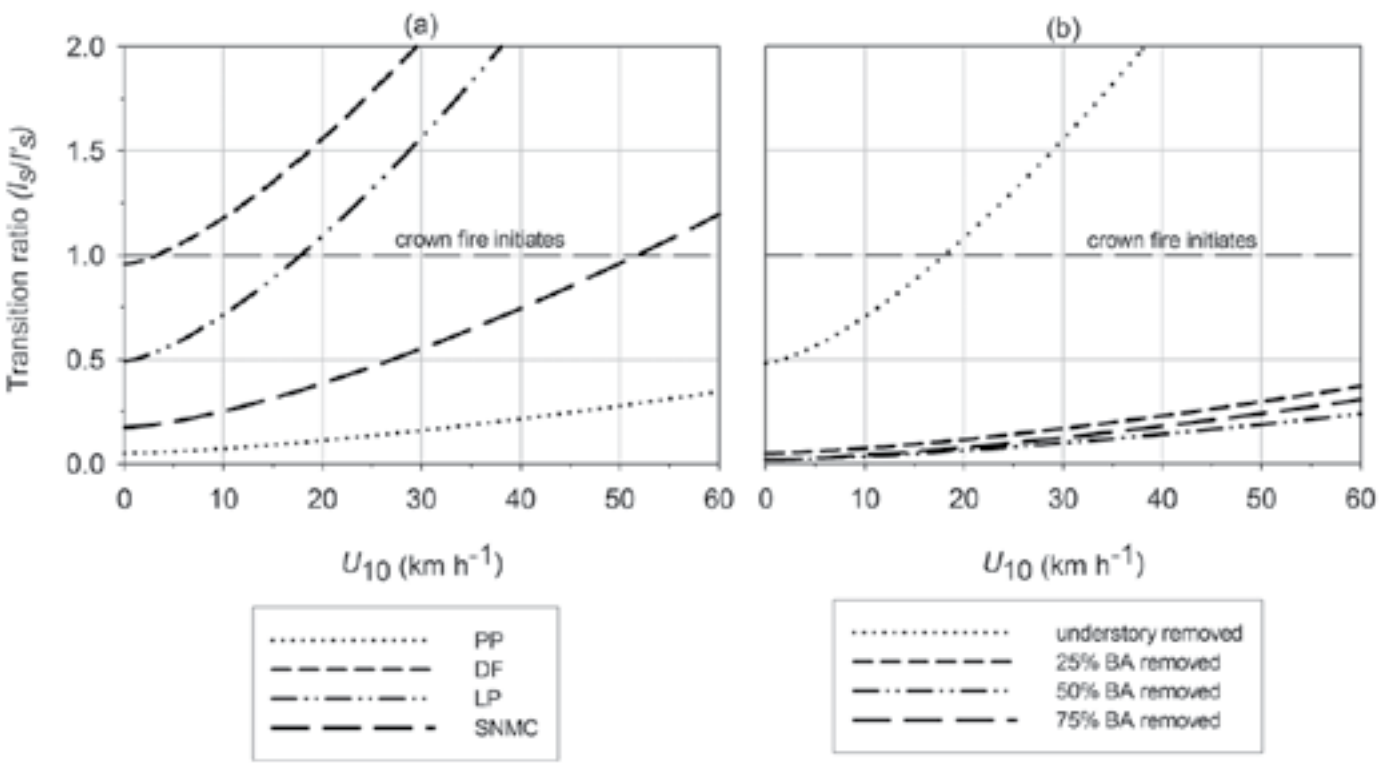

Figure 2—Ratio of predicted to critical fireline intensity (I_s/I'_s) over a range of U_{10} in (a) five different conifer stands, and (b) a ponderosa pine/Douglas-fir stand as basal area (BA) is removed to simulate low thinning. On both charts, the PPDF initial condition is not plotted because *CBH* = 0 m, so the transition ratio is infinity and initiation occurs at any U_{10}. Complete model inputs are described in tables 1 and 2. Forest types include: PPDF = ponderosa pine/Douglas-fir; PP = ponderosa pine; DF = Douglas-fir; LP = lodgepole pine; and SNMC = Sierra Nevada mixed-conifer. Although not part of Van Wagner's (1977) crown fire initiation model, Rothermel's (1972) surface fire spread model, as adjusted by Albini (1976), is used here for predicted fireline intensity (I_s) .

Cruz and others (2004) took a new approach by using logistic regression to predict the probability of observing crown fire behavior (see also Cruz 1999, Cruz and others 2002). The dataset on which the model was built included surface, passive crown, and active crown fires. Rather than predict crown fire initiation (ignition of canopy fuel), the model predicts the probability of observing passive or active crown fire (as opposed to surface fire). Predictive variables include U_{10}, fuel strata gap (*FSG*), surface fuel consumption (*SFC*, kg m^{-2}), and *EFFM*.

Fuel strata gap as conceptually defined by Cruz and others (2004) is identical to the Scott and Reinhardt (2001) definition of *CBH*; both terms refer to the vertical distance from the ground to the height within the canopy at which there is sufficient fuel to propagate fire vertically. Because the terms refer to the same quantity, I will use *CBH* in place of *FSG* because it is used by a majority of the models and systems described. Surface fuel consumption, being a fire characteristic that must be predicted (as opposed to a fuel characteristic that can be observed), is treated as a coded categorical variable (< 1.0, 1.0 – 2.0, and > 2.0 kg m^{-2}). The Cruz model of crown fire occurrence is

$$P_{(crownfire)} = \frac{e^{g(x)}}{1 + e^{g(x)}} \tag{5}$$

where $P_{(crownfire)}$ is the probability of observing some type of crown fire, and

$$g(x) = 4.236 + 0.357U_{10} \quad 0.710CBH - 0.331EFFM \quad SFCfactor \tag{6}$$

where *SFCfactor* is determined from an estimate of *SFC* as follows

***SFC* criteria**	***SFCfactor***
$SFC < 1.0$ kg m^{-2}	4.613
$1.0 < SFC < 2.0$ kg m^{-2}	1.856
$SFC > 2.0$ kg m^{-2}	0.000

The primary output of the Cruz and others model is probability of crown fire occurrence. To use the model deterministically, Cruz and others (2002) apply a threshold probability of 0.5; if $P_{(crownfire)} < 0.5$ then a surface fire is expected; if $P_{(crownfire)} > 0.5$ then crown fire behavior is expected.

Because *EFFM* and *SFC* were assumed to be the same for the initial condition at all sites, variation in $P_{(crownfire)}$ results from variation in *CBH* and U_{10}. The model predicted crown fire in the PPDF initial condition at any wind speed, due to its low *CBH*. In the PP stand, with a *CBH* of 5 m, the model predicted crown fire occurrence if wind speed exceeds 8 km h^{-1} (fig. 3a). Canopy base height rises significantly as the PPDF canopy is opened, but *EFFM* decreases (table 2). In this example, the effect of rising *CBH* was stronger, so crown fire occurrence became less likely as the PPDF stand was opened (fig. 3b).

I assumed a value of *SFC* from the middle category (1 – 2 kg m^{-2}). If *SFC* were actually less than 1 kg m^{-2}, these results would slightly over-estimate the true model predictions.

Sustained Active Crown Fire Spread

There is general agreement on the conceptual validity of a minimum mass-flow rate required for maintaining an active crown fire (Van Wagner 1977). All three surface-crown fire systems discussed here employ that concept. Van Wagner rearranged a basic heat balance equation and theorized that solid flames would form in the canopy space (that is, active crown fire) if a minimum horizontal mass-flow rate of fuel into the flaming zone, *S* (kg m^{-2} min^{-1}), is exceeded

$$S = R_a * CBD \tag{7}$$

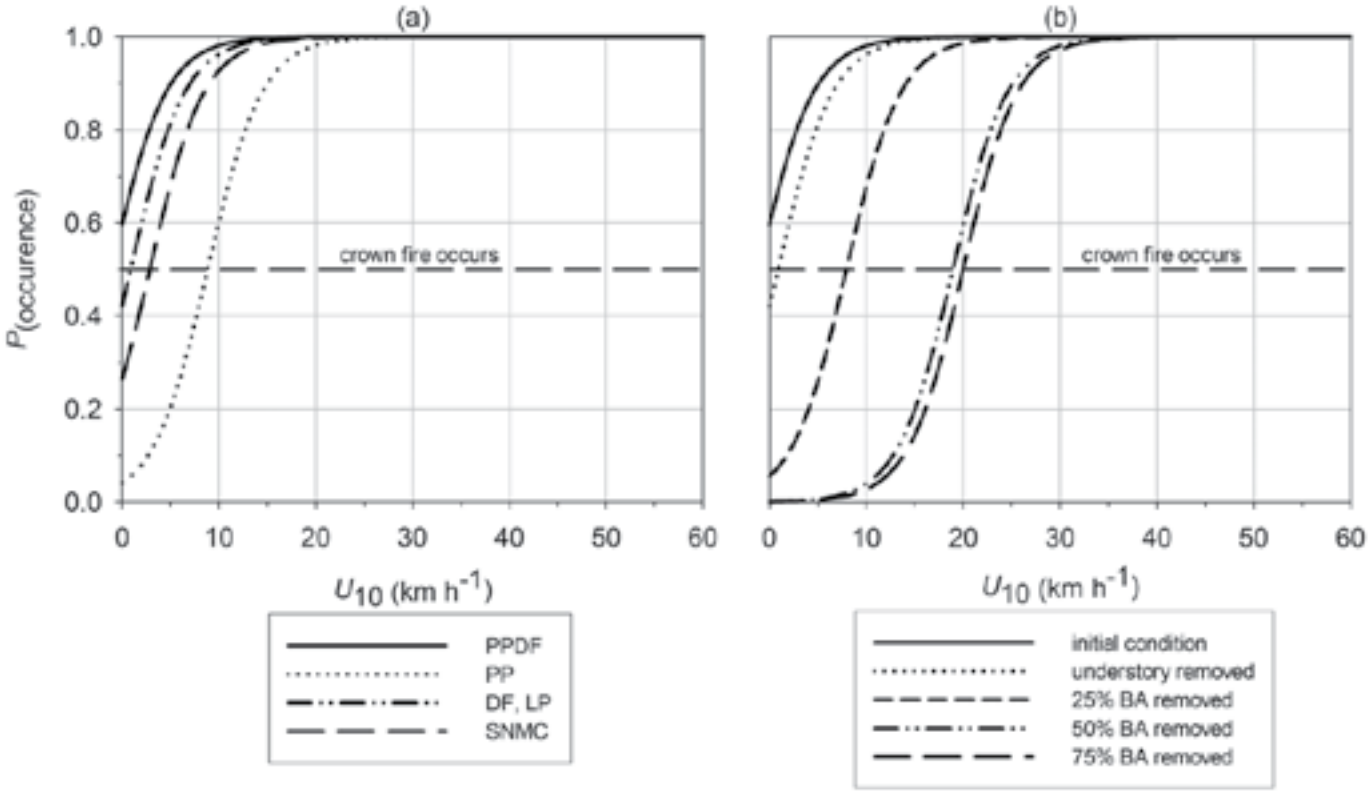

Figure 3 – Probability of crown fire occurrence predicted by the Cruz and others (2004) model over a range of U_{10} in (a) five different conifer stands, and (b) a ponderosa pine/Douglas-fir stand as basal area (BA) is removed to simulate low thinning. Complete model inputs are described in tables 1 and 2. Forest types include: PPDF = ponderosa pine/Douglas-fir; PP = ponderosa pine; DF = Douglas-fir; LP = lodgepole pine; and SNMC = Sierra Nevada mixed-conifer. The DF and LP stands have the same model inputs and are therefore plotted as the same line. Some type of crown fire is said to occur if $P_{(occurrence)}$ = 0.5.

where R_a is the predicted flame front spread rate of an active crown fire spread rate (m min^{-1})° and *CBD* (kg m^{-3}) is the bulk density of canopy fuels available for consumption in the flaming fire front. Van Wagner observed a critical mass-flow rate of 3.0 kg m^{-2} min^{-1} in a red pine plantation, slightly lower but similar in magnitude to the values given by Thomas (1963) for experimental fuelbeds. Substituting 3.0 for *S*, the critical spread rate for active crown fire (m min^{-1}) is

$$R'_a = \frac{3.0}{CBD} \tag{8}$$

An active crown fire is possible for all cases in which potential R_a exceeds R'_a. In estimating the mass-flow rate observation for the above equation, Van Wagner computed *CBD* by dividing canopy fuel load (foliage) by canopy depth, with canopy depth being the difference between stand height and *CBH* (exact method of calculating *CBH* was not specified, and different methods produce very different results, especially when applied to stands with diverse structures). By contrast, the dataset on which these comparisons are based calculated *CBD* as the maximum 3-m vertical running mean through the canopy space, a method which usually produces a slightly higher value than Van Wagner's. Because of that difference, all systems could over-predict mass-flow rate relative to the threshold calculated by Van Wagner. However, comparing the relative behavior of the systems is still valid because the same *CBD* estimation method was used for all systems.

Final (Surface-Crown) Spread Rate

FlamMap and NEXUS employ Van Wagner's (1989, 1993) transition function for scaling spread rate between predictions of surface and crown fire behavior, though the exact implementation varies. Van Wagner called the transition function "crown fraction burned" (*CFB*)—a fraction between 0 and 1 representing the degree of crowning—where 0 indicates no crowning and 1 indicates fully active crown fire. Final spread rate was defined as

$$R_{final} = R_s \quad CFB \quad \left(R_a - R_s\right) \tag{9}$$

For $CFB = 0$ (a surface fire) eq. (9) reduces to $R_{final} = R_s$; for $CFB = 1$ (active crown fire), $R_{final} = R_a$. At intermediate values of CFB, R_{final} is scaled proportionally between R_s and R_a. For example, for $CFB = 0.5$, R_{final} is halfway between the values predicted for R_s and R_a.

The Crown Fire Initiation and Spread (CFIS) surface-crown system does not use the *CFB* concept for determining R_{final} with eq. (9). Instead, passive crown fire spread rate in their system is a function only of R_a and R'_a.

Crown Fire Modeling Systems

FlamMap

FlamMap calculates potential fire behavior across a landscape, incorporating spatial variability in fuels and topography and temporal variability in environmental conditions (wind speed and direction, fuel moisture). FlamMap uses the same surface-crown fire behavior system as FARSITE (Finney 1998). Unlike FARSITE, however, FlamMap does not simulate spotting or spot fire growth, an important distinction. The primary purpose of FARSITE is to predict *where* the fire perimeter will be, and *when*; the *how* (type of fire, fire behavior characteristics) is of secondary importance (though not unimportant). By contrast, FlamMap is not concerned with determining fire perimeter locations, only with mapping *how* a fire might burn a given area.

FlamMap uses the Rothermel (1972) surface fire spread model as adjusted by Albini (1976) for predicting spread rate and intensity of a surface fire. Although FARSITE can utilize surface-fuel-model-specific multiplication factors for adjusting spread rate predictions, FlamMap does not need them because it is not projecting fire growth.

In FlamMap, some kind of crown fire is expected if $I_s > I'_s$ (eq. 4), and surface fire if not. For crown fires, if R_{final} (eq. 9) > R'_a (eq. 8) then active crown fire is expected, otherwise passive crown fire is expected. Passive crown fires are assigned spread rate of
R_s on the reasoning that passive crown fires are controlled by the surface phase (Finney 1998). *CFB* for use in eq. (9) is calculated following Van Wagner (1989), who proposed a transition function of the form

$$CFB = 1 \quad e^{(-ax)} \tag{10}$$

where a is a scaling factor and x is based on the difference between predicted and critical spread rates. In the original Van Wagner model

$$x = R_s \quad R \tag{11}$$

and $a = 0.23$ such that $CFB = 0.9$ when R_s exceeds R'_s by 10 m min^{-1}. R'_s is the spread rate associated with I'_s (eq. 4).

$$R'_s = I'_s\left(\frac{R_s}{I_s}\right) \tag{12}$$

Using eqs. (10) through (12), spread rate transition toward fully active crown fire is independent of the critical or predicted active crown fire spread rate. Depending on surface fuel model and *CBH*, eqs. (10) through (12) can result in low *CFB* even if potential crown fire spread rate indicates active crown fire is possible, and *CFB* can be high even though potential active crown fire spread rate may be well below the minimum needed for active crowning.

Van Wagner (1993) modified the *CFB* equation to permit dynamic calculation of the coefficient *a* to account for variable canopy fuel characteristics. He states that *a* was "based on the difference between [R'_s] and [R'_a], that is, on the difference between the point where crown consumption begins and where it becomes complete" (p. 446). The value of *a* was set such that *CFB* = 0.9 when R_{final} is 90 percent of (R'_a - R'_s)

$$a = \left(\frac{-ln(0.1)}{0.9\left(R'_a - R'_s\right)} \right) \tag{13}$$

Dynamic calculation of the coefficient *a* only partially solves the problem described above where *CFB* is independent of predicted and critical mass-flow rates. FlamMap calculates *CFB* with eqs. (10) through (13).

NEXUS

NEXUS (Scott 1999) was designed for assessing relative crown fire potential by linking separate models of surface and crown fire behavior (Scott and Reinhardt 2001). In addition to predicting surface-crown fire spread and intensity, NEXUS computes indices for rating crown fire potential—Torching Index (TI) and Crowning Index (CI). The TI is defined as the open wind speed (U_{10}) at which the predicted surface fire intensity equals the minimum required for crown fire initiation (Van Wagner 1977). The CI is the U_{10} at which the predicted active crown fire spread rate equals the minimum needed to maintain solid flame through the canopy (Van Wagner 1977).

NEXUS includes an additional type of fire—conditional crown fire—that represents the situation in which the component models predict an active crown fire is possible but initiating one is not. In that case, NEXUS suggests that two outcomes are possible for the conditional crown fire type: surface fire behavior, if fire enters the stand as a surface fire; or active crown fire, if fire enters the stand as a passive or active crown fire (that is, if a crown fire has already initiated).

If R_a (eq. 1) > R'_a (eq. 8) then an active or conditional crown fire is expected, otherwise surface fire or passive crown fire is expected. For active or conditional crown fires, if $I_s > I'_s$ (eq. 4) then NEXUS predicts active crown fire, otherwise conditional crown fire is predicted. For surface fires or passive crown fires ($R_a < R'_a$), if $I_s > I'_s$ then NEXUS predicts passive crown fire, otherwise surface fire.

For all fire types, final spread rate is determined by eq. (9). For conditional crown fires, *CFB* = 1. Otherwise, NEXUS assumes a simple linear transition function

$$CFB = \frac{R_s - R'_s}{R'_{sa} - R'_s} \tag{14}$$

where R'_{sa} is the surface fire spread rate at the environmental conditions for which $R_a = R'_a$. *CFB* must be bounded such that $0 < CFB < 1$.

By default, NEXUS uses Rothermel's average crown fire spread rate model (eq. 1), but can also be set to use Rothermel's near-maximum crown fire spread rate (eq. 2).

CFIS (Crown Fire Initiation and Spread)

The Cruz and others (2005) stepwise process for determining surface-crown spread rate has been implemented in a calculation tool called CFIS V1.0. It uses the Cruz and others (2004) crown fire occurrence model and the Cruz and others (2005) crown fire spread rate model.

If $P_{(crownfire)}$ (eqs. 5 and 6) >0.5 then passive or active crown fire is expected, otherwise surface. For passive or active crown fires, if R_a (eq. 3) > R'_a (eq. 8) then active crown fire is expected, otherwise passive. Surface fires can be given R_s from any (unspecified) model. In CFIS, estimates of surface fire behavior (other than surface fuel consumption) do not affect other model outputs. Although CFIS does not estimate R_s itself, I plotted R_s using Rothermel's (1972) model for FM10, just as for FlamMap and NEXUS. Passive crown fires in CFIS are given a spread rate R_p as follows (Cruz and others 2005)

$$R_p = R_a * e^{-\left(R_a / R'_a\right)} \tag{15}$$

where R_a is from eq. (3) and R'_a is from eq. (8).

Results

Crown Fire Occurrence

Although the FlamMap and NEXUS methods are computationally and theoretically quite different from CFIS, it is nonetheless possible to compare their output by computing TI. Only NEXUS computes TI directly, but each system has an implicit TI. Because FlamMap and NEXUS use the same crown fire initiation models in the same way, their TI values were identical in all cases (fig. 4), ranging from zero for the PPDF initial condition (because *CBH* = 0) to 155 km h^{-1} in the PP stand due to its relatively high *CBH*. The very high value of TI in the PP stand (i.e., TI > 100 km h^{-1}) indicates a very low potential for initiating a crown fire. TI increased quickly as the PPDF stand was opened; with removal of just 25 percent of the initial BA, TI was greater than 100 km h^{-1}, indicating it is nearly impossible to initiate crown fire.

CFIS also implied TI = 0 for the PPDF initial condition. However, it produced much lower values of TI than the other models for all remaining stands (fig. 4a). Where the other systems suggested that crown fire initiation is impossible in the PP stand, CFIS indicated crown fire could occur if U_{10} exceeds only 8 km h^{-1}.

Despite drastic differences in actual values of TI between CFIS and FlamMap/NEXUS, ordinal ranking of crown fire potential in the five stands and five levels of *BA* removal as indexed by TI was similar for all systems.

Potential for Active Crown Fire

Despite diverse implementations of crown fire spread rate models, we can compare how the systems predict the relative ease of sustaining an active crown fire by calculating CI. CFIS predicted the highest active crown fire potential of all the systems (the lowest values of CI). Despite not accounting for the relatively steep slope, CFIS estimated active crown fire would be possible for the DF initial condition if U_{10} exceeds 4 km h^{-1}, whereas NEXUS indicated CI of 23 km h^{-1} (fig. 5). The implied FlamMap CI was much higher than both NEXUS and CFIS, 55 km h^{-1} for the DF initial condition. For all stands and levels of simulated treatment, FlamMap CI was at least twice that of NEXUS, and roughly eight times that of CFIS (fig. 5).

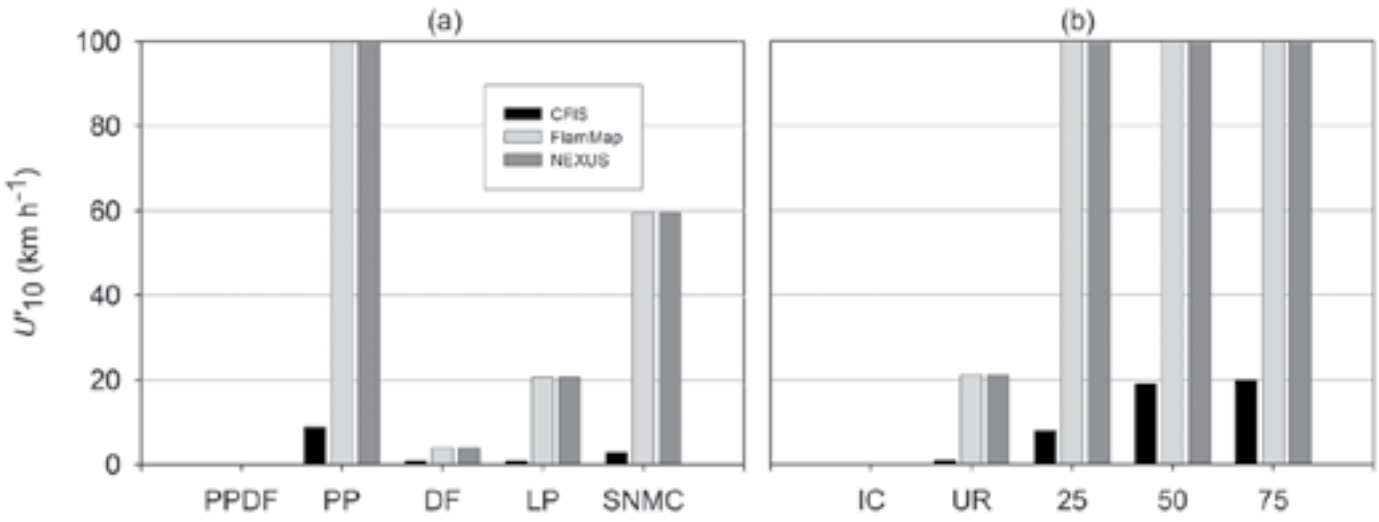

Figure 4—Torching Index (TI), defined as the open wind speed (U'_{10}) at which different surface-crown systems predict crown fire initiation or occurrence, for (a) five different conifer stands, and (b) a ponderosa pine/Douglas-fir stand as basal area (BA) is removed to simulate low thinning. Complete model inputs are described in tables 1 and 2. High values of U'_{10} indicate low potential for crown fire initiation or occurrence. Forest types include: PPDF = ponderosa pine/Douglas-fir; PP = ponderosa pine; DF = Douglas-fir; LP = lodgepole pine; and SNMC = Sierra Nevada mixed-conifer. Simulated BA reduction levels include: IC = initial condition; UR = understory removal (all trees < 5 cm dbh); 25 = 25 percent of initial BA removed; 50 = 50 percent BA removal; and 75 = 75 percent BA removed. Y-axis is truncated at U_{10} = 100 km h^{-1}. Wind speeds above 100 km h^{-1} occur so rarely that crown fire can be considered nearly impossible to initiate for U_{10} > 100 km h^{-1}.

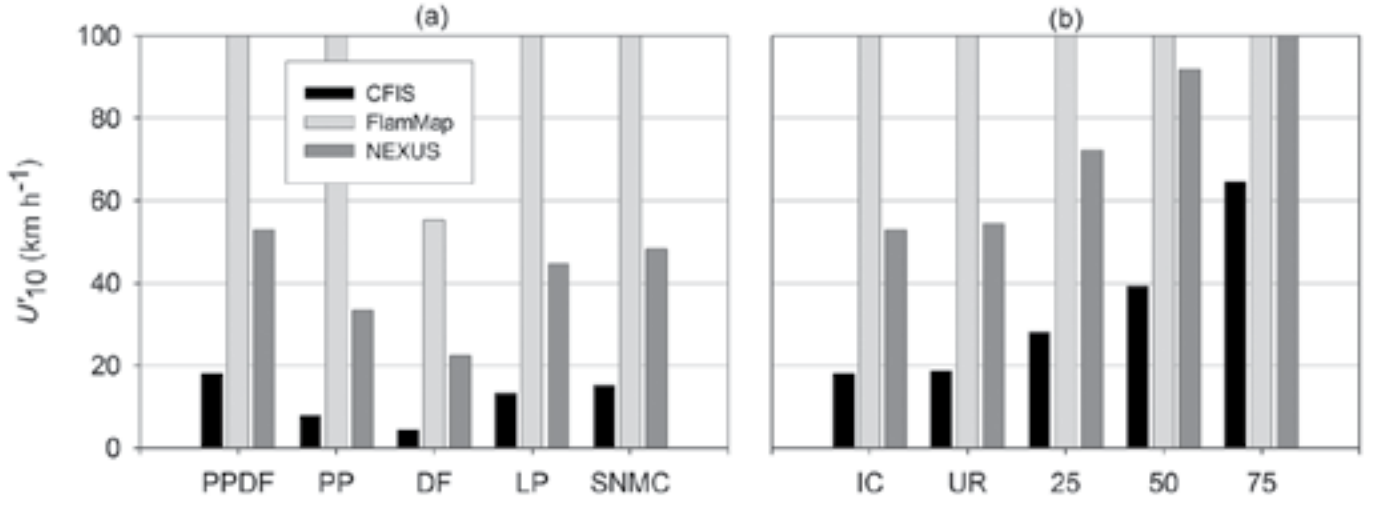

Figure 5—Crowning Index (CI), defined as the open wind speed (U'_{10}) at which active crown fire spread is possible, for (a) five different conifer stands, and (b) a ponderosa pine/Douglas-fir stand as basal area (BA) is removed to simulate low thinning. Complete model inputs are described in tables 1 and 2. High values of U'_{10} indicate low potential for active crown fire spread. Forest types include: PPDF = ponderosa pine/Douglas-fir; PP = ponderosa pine; DF = Douglas-fir; LP = lodgepole pine; and SNMC = Sierra Nevada mixed-conifer. Simulated BA reduction levels include: IC = initial condition; UR = understory removal (all trees < 5 cm dbh); 25 = 25 percent of initial BA removed; 50 = 50 percent BA removal; and 75 = 75 percent BA removed. Y-axis is truncated at U_{10} = 100 km h^{-1}. Wind speeds above 100 km h^{-1} occur so rarely that active crown fire can be considered nearly impossible to sustain for U_{10} > 100 km h^{-1}.

Again, despite drastic differences in actual values of CI, ordinal ranking of crown fire potential based on CI was similar for the three systems. Only FlamMap deviated from the others, and then only in the ranking of the PPDF and PP stands. FlamMap's highest CI occurred in the PP stand, whereas the other systems predicted the highest CI in the PPDF stand (because it has the lowest *CBD*). This occurred because of the effect of the PP stand's high *CBH* on *CFB* as computed with eqs. (10) through (13). Despite the PPDF stand having the lowest *CBD*, FlamMap assigned it a moderate CI because of its very low *CBH*.

Because all systems are using the same R'_a threshold (Van Wagner 1977), variation in CI among systems arises from the calculation of R_a. The Cruz and others (2005) model used in CFIS predicts the highest crown fire spread rates, therefore CFIS produced the lowest values of CI. The relatively high values of CI in FlamMap result from two factors:

- calculation of *CFB* independent of R_a and R'_a
- reduction of R_a by *CFB* (eq. 9) *before* comparing R_{final} against R'_a

By directly using eqs. (10) through (13), FlamMap's calculation of *CFB* does not depend greatly on *CBD* or R_a. Instead, *CFB* is primarily a function of predicted *surface fire* spread rate, available surface fuel, and *CBH*. FlamMap *CFB* never exceeds 0.4 in any of the stands, even at very high wind speeds (fig. 6). As *CBH* increases with treatment in the PPDF stand (table 2), *CFB* is reduced further; by the time 25 percent of the initial BA has been removed, *CFB* never rises above zero at U_{10} less than 60 km h^{-1}. Although *CBD* is also falling with treatment, it has little effect on the reduction in *CFB*. The only effect of *CBD* on *CFB* is though calculation of the parameter *a* (eq. 13).

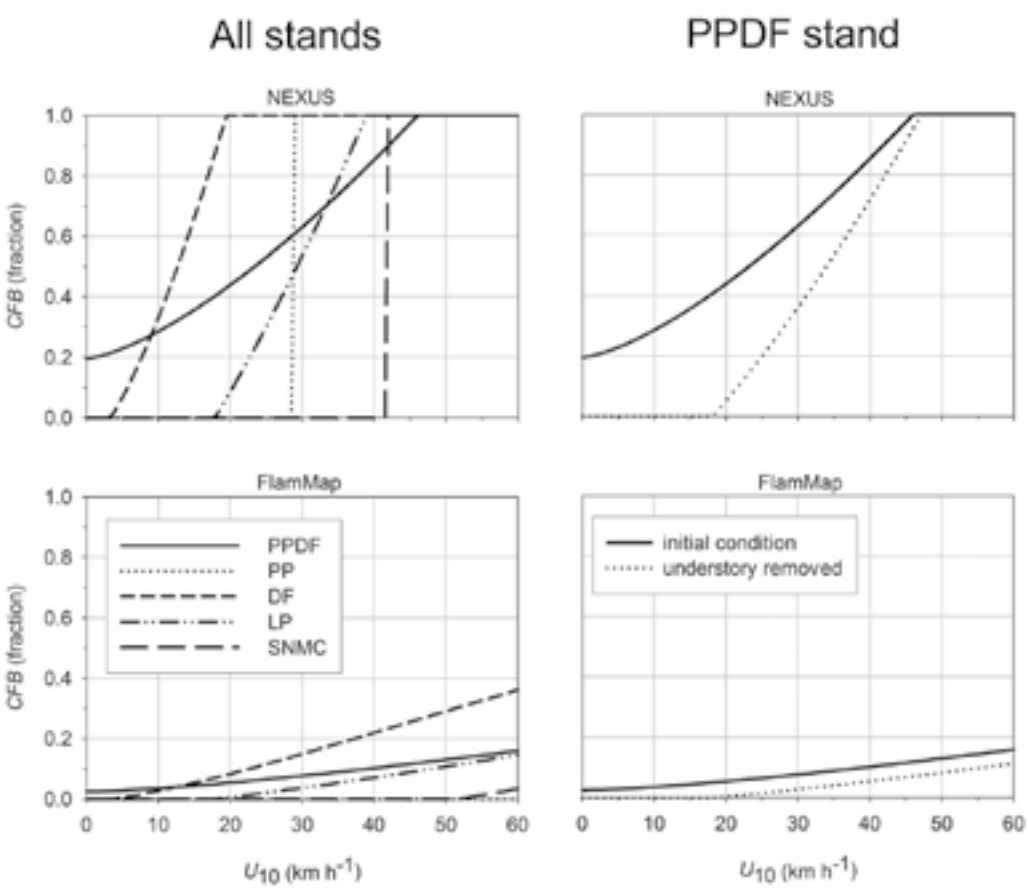

Figure 6—Crown Fraction Burned (*CFB*) as calculated in NEXUS and FlamMap for the initial condition at five conifer sites (left charts), and at the PPDF site at progressive levels of treatment (right charts). After 25 percent of the initial BA was removed from the PPDF stand, both FlamMap and NEXUS predicted *CFB* = 0.

FlamMap computes R_{final} by eq. (9) and *CFB* as calculated above, then compares R_{final} against R'_a to see if an active crown fire is possible. Of the three systems, only FlamMap applies the *CFB* reduction *before* determining whether an active crown fire is possible; the others compare R_a against R'_a. Because the FlamMap *CFB* calculation results in relatively small values, the result is lower potential crown fire spread rate compared to NEXUS.

Type of Fire

All systems classify type of fire as surface, passive crown, or active crown fire. In addition to these fire types, NEXUS includes a *conditional crown fire* type, which represents a situation in which an active crown fire is possible ($R_a > R'_a$), but one would not be predicted to initiate ($I_s < I'_s$, or $P_{(\text{occurrence})} < 0.5$ in CFIS). Two outcomes are possible in that situation: surface fire if the fire starts in the stand as a surface fire, or active crown fire if fire enters the stand as an active crown fire (for example, if a crown fire has initiated elsewhere and spread into the stand of interest). All other systems classify that situation as a surface fire. NEXUS reports the spread rate of a conditional crown fire as if it were an active crown fire. (The original spreadsheet version of NEXUS classified this situation as a conditional *surface* fire and reported spread rate as if it were a surface fire.)

CFIS predicted active crown fire in all five stands for $U_{10} > 18$ km h^{-1}, whereas FlamMap predicted active crown fire only in the DF stand, and then only for $U_{10} > 55$ km h^{-1} (fig. 7a).

All systems showed progressive reduction in passive and active crown fire as *BA* was removed from the PPDF stand (fig. 7b), though CFIS showed a lesser reduction than the other systems.

Final Rate of Spread

All aspects of how each system simulates surface-crown fire behavior are expressed in predictions of R_{final} over a range of U_{10} (figs. 8 and 9). Note that all systems use the same R'_a threshold to distinguish active crowning. The primary difference among the systems is how each predicts R_a for comparison with R'_a.

In five conifer stands—For the PPDF initial condition, all systems predicted crown fire is possible even with no wind. CFIS predicted passive crown fire spread rate for the region $0 < U_{10} < 18$ km h^{-1}, then active crown fire at higher wind speeds (fig. 8). In the passive crown fire range, R_{final}, as computed with eq. (15), asymptotes to the value R'_a * 0.37, then jumps to R'_a and follows R_a for $U_{10} > 18$ km h^{-1}. NEXUS predicted passive crown fire for the region $0 < U_{10} < 53$ km h^{-1}, then active crown fire at higher wind speeds. FlamMap predicted passive crown fire for the entire region $0 < U_{10} < 60$ km h^{-1}. For passive crown fires in FlamMap, $R_{final} = R_s$.

For the PP stand, CFIS predicted surface fire for the region $0 < U_{10} < 9$ km h^{-1}, then active crowning at higher wind speeds. Note that there is no region of passive crowning because the wind speed at which active crowning is possible (8 km h^{-1}) is less than that for which crown fire was predicted to initiate. NEXUS predicted surface fire for the region $0 < U_{10} < 33$ km h^{-1}, then conditionally active crown fire spread rate at higher wind speeds. FlamMap predicts surface fire spread for the entire range $U_{10} < 60$ km h^{-1} because $I_s < I'_s$ for that range.

In the DF stand, CFIS predicted passive crown fire for the region $1 < U_{10} < 4$ km h^{-1}, with surface fire at lower wind speed and active crown fire at higher wind speeds. In the passive crown fire region, R_{final} asymptoted to 4.3 m min^{-1}, then jumped to R_a. NEXUS predicted passive crown fire spread for the region $4 < U_{10} < 22$ km h^{-1}, with surface spread at lower wind speeds and active crown fire spread at higher wind speeds. FlamMap

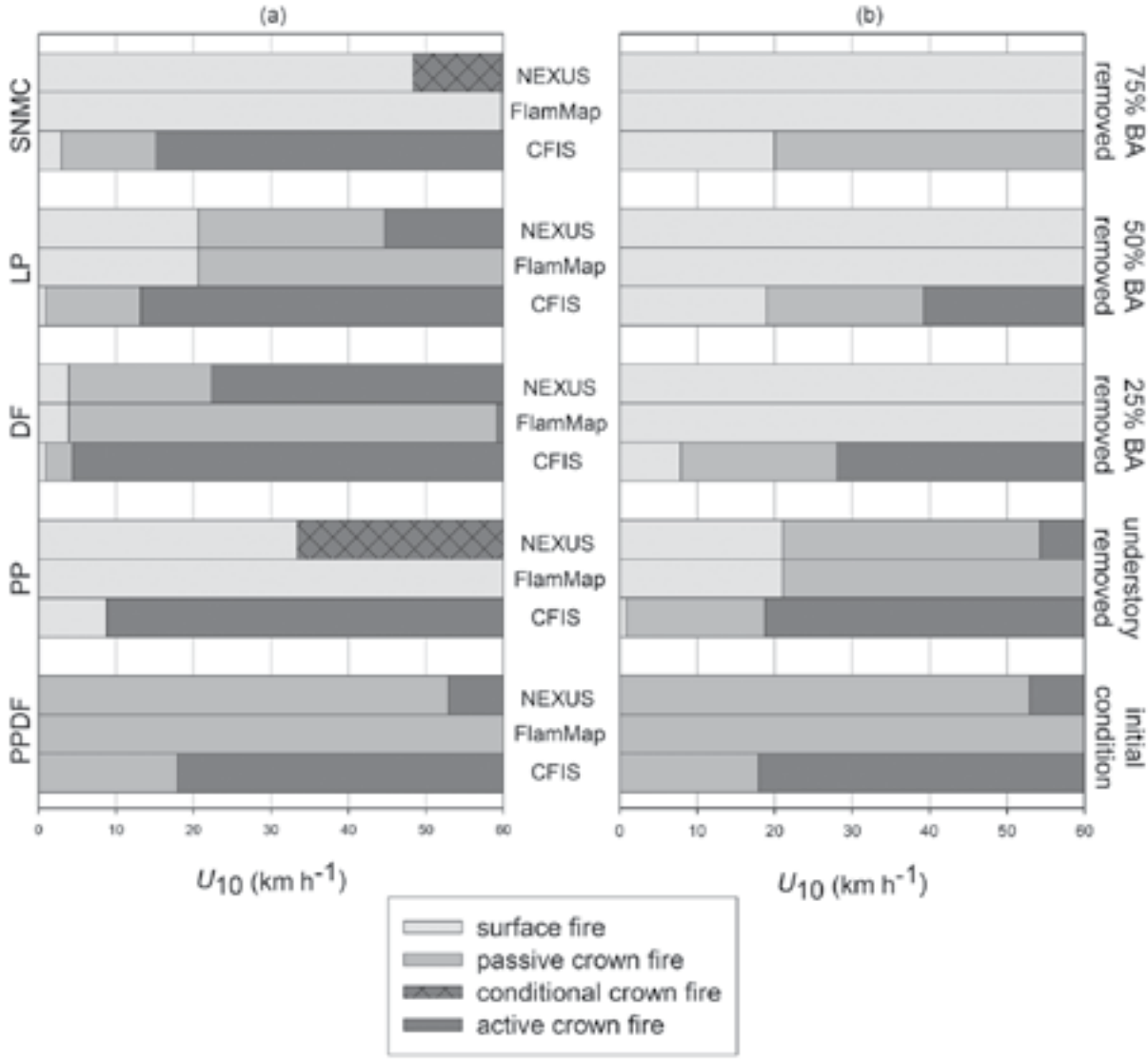

Figure 7—Predicted type of fire for (a) five different conifer stands, and (b) a ponderosa pine/Douglas-fir stand as basal area (BA) is removed to simulate low thinning. Complete model inputs are described in tables 1 and 2. Forest types include: PPDF = ponderosa pine/Douglas-fir; PP = ponderosa pine; DF = Douglas-fir; LP = lodgepole pine; and SNMC = Sierra Nevada mixed-conifer. Simulated BA reduction levels include: IC = initial condition; UR = understory removal (all trees < 5 cm d.b.h.); 25 = 25 percent of initial BA removed; 50 = 50 percent BA removal; and 75 = 75 percent BA removed.

predicted passive crown fire spread for the range $4 < U_{10} < 55$ km h^{-1}. Because FlamMap assigns R_s to passive crown fire spread rate, $R_{final} = R_s$ for the whole range $0 < U_{10} < 55$ km h^{-1}, above which R_{final} is computed using eqs. (9) through (13).

In the LP stand, CFIS predicted passive crown fire for the wind speed range $1 < U_{10} < 13$ km h^{-1}, with surface spread below and active crown fire spread above that range. Passive crown fire spread rate asymptotes to 9.9 m min^{-1}. NEXUS predicted passive crown fire spread in the range $21 < U_{10} < 45$ km h^{-1}, with surface spread below and active crown fire spread above that range. FlamMap predicted passive crown fire spread in the range $21 < U_{10} < 60$ km h^{-1}, with surface spread below that range. $R_{final} = R_s$ over the whole range $0 < U_{10} < 60$ km h^{-1}.

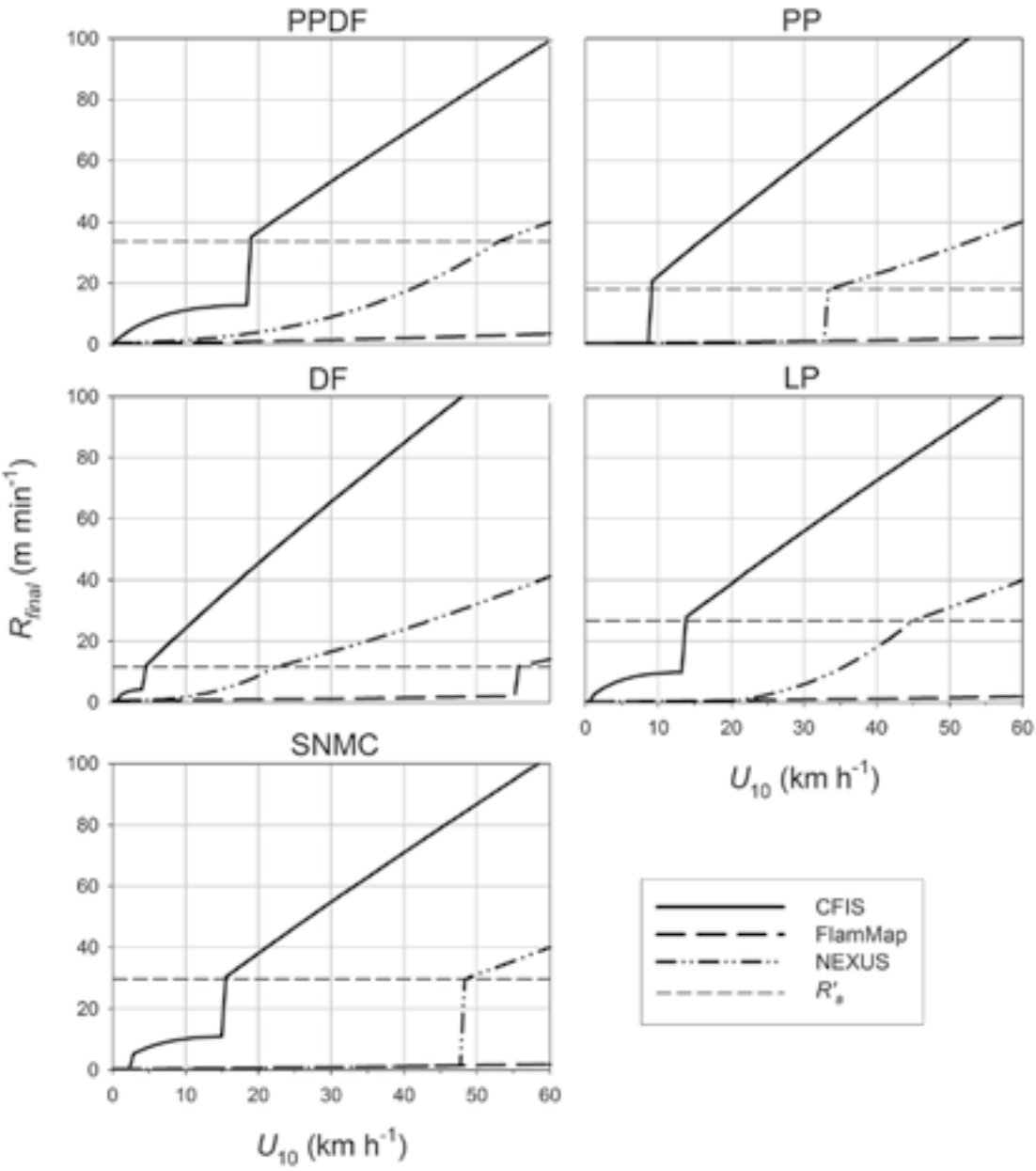

Figure 8—Final (surface-crown) spread rate predicted by CFIS, FlamMap, and NEXUS for five different conifer stands. Complete model inputs are described in table 1. Forest types include: PPDF = ponderosa pine/Douglas-fir; PP = ponderosa pine; DF = Douglas-fir; LP = lodgepole pine; and SNMC = Sierra Nevada mixed-conifer. R'_a is the minimum spread for maintaining active crown fire.

In the SNMC stand, CFIS predicted passive crown fire for the range $3 < U_{10} < 15$ km h^{-1}, with surface spread below and active crown spread above that range. Passive crown fire spread rate asymptotes to 12.5 m min^{-1}. The initial value for passive crown fire spread rate is computed independent of surface fire spread rate (eq. 15), so spread rate jumps abruptly at both TI and CI. NEXUS predicted surface fire spread for $U_{10} < 48$ km h^{-1}, with conditionally active crown fire spread above that range. FlamMap predicted surface fire spread for $U_{10} < 59$ km h^{-1}, with passive crown fire spread (for which $R_{final} = R_s$) above that range.

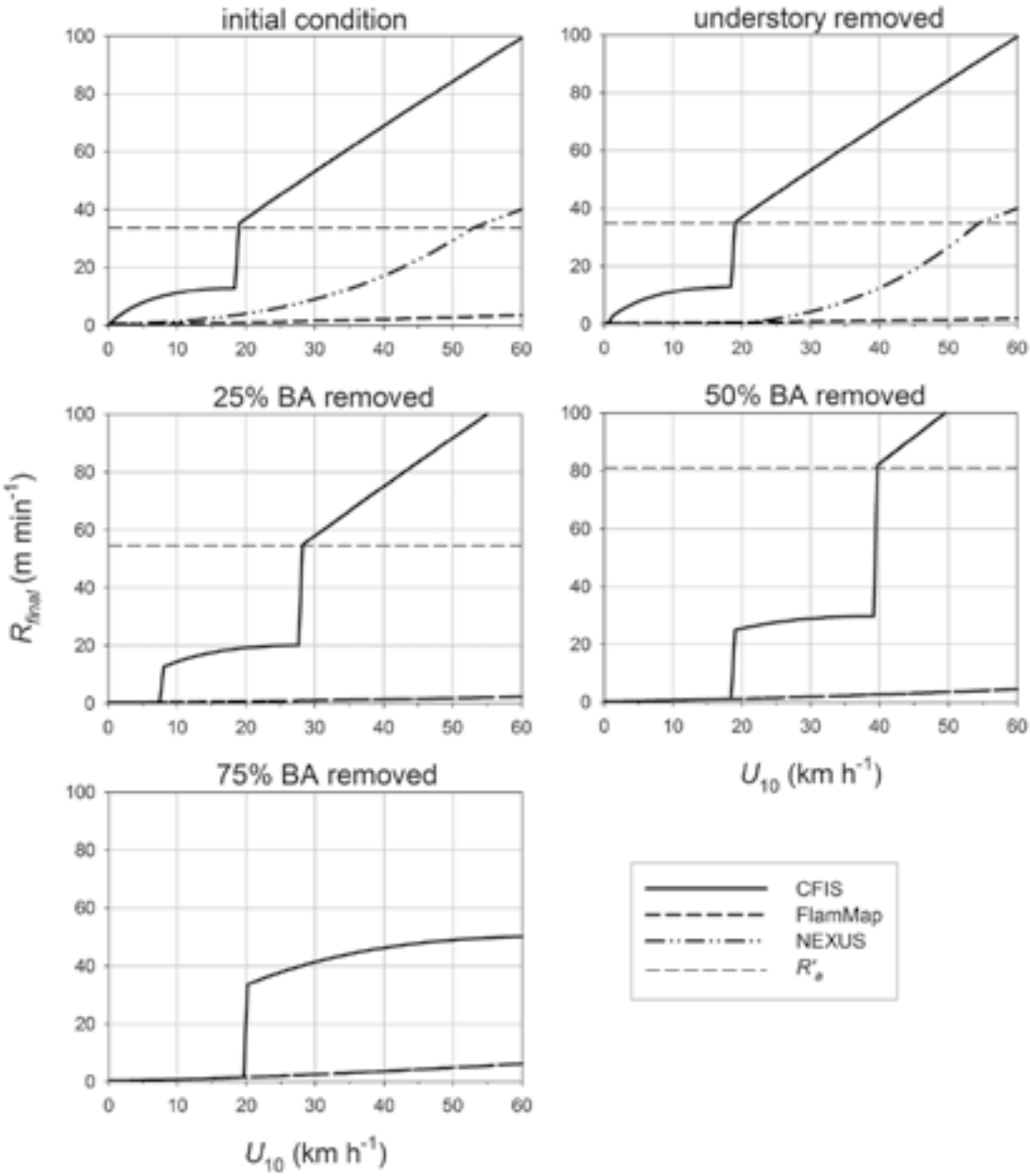

Figure 9—Final (surface-crown) spread rate predicted by CFIS, FlamMap, and NEXUS for a ponderosa pine/Douglas-fir stand as basal area (BA) is removed to simulate low thinning. Complete model inputs are described in table 2. R'_a is the minimum spread for maintaining active crown fire; for 75 percent BA removed, R'_a is 136 m min^{-1}.

Following simulated treatments—Using CFIS, predicted R_{final} changed little after removal of the understory in the PPDF stand. In the remaining systems, surface fire spread was then predicted for $U_{10} < 21$ km h^{-1}, with passive or active spread above that range (fig. 9).

After removal of 25 percent of the initial BA, CFIS then predicted passive crown fire for the range $8 < U_{10} < 28$ km h^{-1}, with surface spread below and active crown spread above that range. The values for passive crown fire spread rate began at 13 m min^{-1} and asymptoted to 20 m min^{-1}. NEXUS and FlamMap both predicted surface fire spread for $U_{10} < 60$ km h^{-1}, because $I_s < I'_s$ for that range.

After removal of 50 percent of the initial BA, CFIS predicted passive crown fire spread for the range $19 < U_{10} < 39$ km h^{-1}, with surface spread below and active spread above that range. The values for passive crown fire spread rate began at 25 m min^{-1} and asymptoted to 30 m min^{-1}. All other systems predicted surface fire spread for $U_{10} < 60$ km h^{-1}, because $I_s < I'_s$ for that range.

After removal of 75 percent of the initial BA, CFIS predicted passive crown fire spread for $U_{10} > 20$ km h^{-1}, with surface spread below that range. The values for passive crown fire spread rate began at 34 m min^{-1} and asymptoted to 50 m min^{-1} (which would be reached at $U_{10} = 65$ km h^{-1}). All other systems predicted surface fire spread for $U_{10} < 60$ km h^{-1}, because $I_s < I'_s$ for that range.

Discussion

Although the surface-crown modeling systems in CFIS, FlamMap, and NEXUS are all designed to predict the same basic fire behavior characteristics (fire type, spread rate), their results for the same fire environment differ considerably. Across the range of inputs used in these comparisons, CFIS predicts the highest incidence of crown fire and the highest resulting spread rates, whereas FlamMap predicts the lowest crown fire incidence and lowest spread rates. NEXUS outputs fall between those two systems.

The FlamMap and NEXUS surface-crown modeling systems are very similar in architecture, but subtle differences in implementation lead to significantly less predicted crown fire activity in FlamMap than NEXUS. Those differences arise from two sources: (1) in FlamMap, passive crown fire flame front spread rate is set to that of the surface fire, whereas NEXUS follows Van Wagner (1993) by estimating passive crown fire spread rate by scaling between surface and crown fire spread rates; and (2) the FlamMap method of calculating *CFB* results in much lower values than NEXUS, resulting in lower predictions of crown fire spread rate. Even under high to extreme environmental conditions in dense stands, *CFB* as computed in FlamMap rarely rises to 0.5, whereas an active crown fire would logically have *CFB* near 1.0. Therefore, FARSITE and FlamMap users are accustomed to adjusting fire environment characteristics in order to obtain accurate simulation results. For example, it is common to use higher open wind speeds, higher *CBD*, or lower *CBH* than observed in order to force a simulation to predict the higher spread rates associated with active crown fire. In FARSITE, where the primary purpose is to predict fire front location, the simulation of ember transport and spot fire growth can compensate for any possible under-prediction of crown fire spread rate by increasing overall fire growth. This spotting mechanism is not present in FlamMap. Spread rate and intensity of active crown fire, in the few situations where FlamMap predicts it will occur, are much lower than the Cruz and others (2005) model, and are usually lower than the Rothermel (1991) model upon which it is built.

CFIS output is notable for its comparatively high incidence of crown fire and subsequent crown fire behavior. Fully active crown fire in CFIS is predicted to have spread rates even greater than Rothermel's near-maximum spread rates. Clearly, the difference in scale between data used to develop each model must play a role in explaining this difference. Even the relatively short-duration crown fire runs used in Rothermel's near-maximum spread model were much larger and longer than the experimental crown fires used in building the model used in CFIS. In the Rothermel near-maximum model, duration and extent are long enough that the fire environment cannot reasonably be assumed constant—factors such as slope steepness, surface and canopy fuel characteristics, and wind speed and direction may have varied within the run, so it is difficult to associate the observed behavior with a specific fire environment. The experimental fires in the Cruz and others (2005) dataset are small enough that fire environment *can* be assumed constant, but their small size may preclude direct

application to real crown fires. Those experimental fires were in units whose sides were just a few tree-heights in length, and even fewer flame-heights. To contain the experimental fires, wide areas around each unit were necessarily cleared of trees, resulting in drastic change in wind flow into the burn unit from all sides. A free-burning line fire in the same conditions might, therefore, exhibit lower spread rate.

The CFIS final spread rate system exhibits curious behavior as wind speed increases, especially for higher values of *CBH* (figs. 8 and 9). In such cases, abrupt changes in spread rate occur at both the surface-passive and passive-active transitions (TI and CI). Passive crown fire spread rate depends on predicted and critical active crown fire spread rates (R_a and R'_a), but not on surface fire spread rate. The CFIS passive crown fire spread rate equation form leads to an initial rapid rise in R_{final}, then a gradual increase as R approaches R'_a asymptotically. At the point where predicted active crown fire equals the critical value ($R_a = R'_a$), passive crown fire spread rate = 0.37 * R'_a, due to the assumed form of the passive crown fire equation. This predicted behavior appears to be an artifact of the system rather than intentional design, as the authors offer no physical explanation for the behavior.

Because NEXUS is designed to assess crown fire potential of different stands and treatments, it would be more appropriate to use Rothermel's near-maximum crown fire spread rate model rather than the long-range average, as is currently used. Doing so would reduce the chance of under-predicting crown fire potential (NEXUS can emulate the use of Rothermel's maximum spread rate model by setting ROSMhigh to 1.7.) Switching to the near-maximum model would not affect TI, but would reduce computed values of CI, indicating higher potential for crown fire, and would also predict higher potential passive and active crown fire spread rates. CFIS, however, would still predict even greater crown fire potential that NEXUS with the near-maximum model.

Management Implications

CFIS, FlamMap, and NEXUS predict very different surface-crown fire behavior for the same fire environment. Despite the significant differences in crown fire behavior predictions, the ordinal ranking of crown fire potential (by implicit TI and CI) in the five stands and five treatments is similar among the three systems, so users can rely on the relative fire behavior potential estimated from any of the systems. However, absolute fire potential, not just the relative potential among stands, is critical for many fire management applications such as determining acceptable levels of hazard, prioritizing areas for fuel treatment, and quantifying the benefit of fuel treatments. Therefore, the output from these systems must be compared with observation and experience to determine the suitability of the system.

FlamMap and NEXUS were built on the same component fire behavior models, but minor differences in implementation (the calculation of *CFB*) lead to very different simulation results. For the same independently determined fire environment characteristics, FlamMap under-predicts the incidence and behavior of active crown fire compared to NEXUS.

The FlamMap surface-crown fire modeling system is identical to that of FARSITE, which has a different primary purpose (fire growth simulation vs. fire potential mapping). Unlike FARSITE, however, FlamMap does not simulate the effects of ember transport and spotting on overall fire growth, and therefore under-predicts the effects of crown fire on fire growth compared to FARSITE.

CFIS and NEXUS were built on different component models, which were in turn built with different types of data gathered at different scales. It is not surprising, then, that those systems predict very different fire behavior for the same fire environment inputs. An individual user has no control over which system is used in a particular application; these

comparisons cannot be used to select the appropriate system. However, these comparisons may be useful in determining inputs and interpreting output from the different systems, and perhaps in the development of future surface-crown fire modeling systems.

Finally, this analysis compares the modeling systems only with each other, not with "the truth;" we do not know the truth. From this analysis alone, one cannot conclude that a particular system or approach is necessarily any better or more accurate than another, just *how* and *why* their results are different. The spread rate modeling systems described and compared here are artful applications of existing knowledge; they do not attempt to explain the physics or mechanics of crown fire initiation and spread. As the science of surface and crown fire behavior advances, so too will our fire management applications.

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