Quantifying Stand Targets for Silvicultural Prevention of Crown Fires

Christopher R. Keyes, *Department of Forestry and Watershed Management, Humboldt State University, Arcata, CA 95521-8299 and* **Kevin L. O'Hara,** *Division of Forest Science, 145 Mulford Hall, University of California, Berkeley, CA 94720-3114.*

ABSTRACT: *Forest managers are expressing a growing interest in proactively reducing susceptibility to crown fires, but the quantitative basis for defining specific stand targets and prescribing silvicultural regimes for this objective is lacking. A procedure is presented for creating resistant stand structures that exploits the relationship between crown fire development and characteristics of stand structure. The BEHAVE surface fire model was integrated with modified versions of the Van Wagner crown ignition and crown fire spread equations in order to quantify structural targets for mitigative silvicultural practices. The procedure tolerates an array of input data types for weather, site, and surface fuel variables so that hazard-reducing guidelines are tailored to specific site and stand conditions. Suggested strategies for achieving crown fire-resistant stand targets include pruning, low thinning, and surface fuel management. West. J. Appl. For. 17(2):101–109.*

Key Words: Fire models, fuel-reduction recommendations, fire surrogates, crown fires, fire hazard.

Silviculturists today are called on to design forest stand structures for an increasingly expanding array of objectives (O'Hara et al. 1994). One of these objectives is the prevention of catastrophic crown fires, high-intensity wildfires that advance through a stand's canopy and kill trees in the process. Crown fires exhibit violent behaviors, are difficult and dangerous to suppress, and cause great economic damage and ecological disruption. They begin as surface fires that climb into the canopy if the stand's crown structure enables this transition (Van Wagner 1977). Since manipulation of stand structure is the fundamental basis of silviculture, it follows that foresters have the ability to directly affect a stand's susceptibility to crown fire. However, silvicultural tools were traditionally constructed largely out of the need to produce wood crops, not prevent high-intensity wildfires, and quantitative methods necessary for creating and maintaining stands that are resistant to crown fires are lacking. Managers need a method that will enable them to identify target structures that can be achieved with silvicultural practices operating at the stand level. For this objective, a flexible system is required in which the factors that influence crown fire hazard can be adjusted to reflect the characteristics of specific stands.

The crown fire model produced by Van Wagner (1977) provides a means to quantitatively assess crown fire potential for existing surface fuel and stand structure conditions. Although it has not been extensively tested, the Van Wagner model has gained wide acceptance by the fire science community and has been adopted in the latest generation of fire behavior and fire spread prediction software (Finney 1998, Andrews and Bevins 1999, Scott 1999). The model was advanced as a tool for predicting the crown fire potential of existing stands (Van Wagner 1989, Van Wagner 1993). Used in that manner, the model can help prioritize stands for treatment on the basis of hazard. It has also been used in a limited way in studies that have simulated crown fire hazard in response to generalized silvicultural systems and treatments (Johnson et al. 1998, Stephens 1998, Wilson and Baker 1998, Graham et al. 1999). The NEXUS spreadsheet application (Scott 1999) utilizes the Van Wagner model to enable users to explore the stand-level links between surface and crown fire behavior. However, NEXUS assumes that users possess a solid understanding of fire behavior and fire modeling methods.

We describe here a simple procedure that integrates the BEHAVE surface fire behavior model (Andrews 1986) and Van Wagner (1977) crown fire model for the construction of quantitative silvicultural guidelines to reduce stand crown fire hazard. The models used in this system are not new; rather, they are familiar to fire scientists and many fire managers. However, this procedure may be useful to a broader spectrum of resource managers who are interested in protecting stands from crown fires. We used it to establish

NOTE: Christopher Keyes can be reached at (707) 826-5484; Fax: (707) 826-5634; E-mail: crk6@humboldt.edu. The method described here was developed for a study supported by the U.S. Environmental Protection Agency. The authors thank Ron Wakimoto and Kevin Ryan for their contributions to that study, and Scott Stephens, Jim Long, and an anonymous reviewer for their helpful comments on this article.

silvicultural guidelines for reducing crown fire hazard in the primary forest types of the northern Rocky Mountains (Keyes 1996), but the method is applicable to a much wider range of conifer forest types.

Methods

Procedure Overview

The Van Wagner (1977) crown fire model depicts crown fire occurrence as the result of certain surface fuel, crown fuel, and environmental conditions. The model distinguishes among three types of crown fire: independent, passive, and active. The independent type, an intense crown fire that fuels its own spread and has become independent of the surface fire, occurs only under extreme circumstances. Much more common are the passive and active types, which remain dependent on the behavior of the surface fire. In the passive type, flames spread from the surface fire to the canopy, but do not spread consistently among trees. In the active type, flames spread from crown to crown, surface and crown fire elements advance together as an interdependently linked unit, and firebrands from the burning crowns create spot fires that advance the surface fire beyond its normal rate of spread.

Two stand structure variables are present in the Van Wagner (1977) crown fire model that can be affected by silvicultural activities to reduce susceptibility to crown fire. Crown base height determines whether surface fires can climb into tree crowns, referred to as "crown ignition." Crown bulk density determines whether crown fire spread, or the horizontal transfer of fire between crowns, can occur. This section briefly outlines the procedure for customizing the crown base height and crown bulk density targets for individual stand and site conditions (Figure 1). The necessary inputs and calculations are discussed briefly and are more fully explained in following sections. Later we discuss strategies for implementing the calculated targets in silvicultural prescriptions. In this procedure, a basic familiarity with use of the BEHAVE surface fire behavior model by the reader is assumed.

Within the broad goal of increasing stand resistance to crown fires, forest managers must specify which objective best describes their situation: (1) preventing crown fires from starting in stands that are subjected to prescribed burning or natural low-intensity fires or (2) protecting stands against crown fires spreading from an adjacent stand. Managers conducting restoration burns, for example, can use the crown ignition model to specify a crown base height for preburning activities that will prevent escalation of the prescribed fire. Managers interested in a more complete crown fire prevention strategy—for example, establishing stands that resist crown fire initiation and cause crown fire cessation—need be concerned with a stand's crown bulk density as well as its crown base height. Because of the extra difficulty in specifying a silvicultural target for crown bulk density and the extra costs in achieving and maintaining that structure, managers must determine which of these two strategies best fits their goals and constraints.

For designing a stand that is resistant to crown ignition (Objective 1), surface fuel and environmental data are utilized in BEHAVE to predict surface fire behavior. Foliar moisture content and the fireline intensity predicted by BEHAVE are integrated in Equation (1). These are compared to the stand's actual crown base height. If the actual height exceeds the target height, then the stand is already resistant to crown ignition, and no further actions are necessary. If the crown base height is too low, then some mitigative action is necessary. The silvicultural practices to alter crown base height are simulated, and residues from those treatments are added to the current fuel load. If surface fuel reduction treatments such as prescribed burning are planned, then their effects on the fuelbed are also simulated. The procedure is executed again with the projected post-treatment fuelbed and is repeated until the simulations yield a crown base height that exceeds the target height.

For designing a stand that is resistant to crown ignition and spreading crown fires (Objective 2), the steps described for Objective 1 are carried out. Once the target crown base height is determined, BEHAVE is used with different input parameters (described below) to determine a target crown bulk density via Equation (3). The target crown bulk density is then compared to the stand's actual crown bulk density. If the actual density is less than the target density, then the stand is already resistant to crown fire spread and no further actions are necessary. If the actual crown bulk density is too great, then some mitigative action is necessary. The silvicultural practices to alter crown base height and crown bulk density are simulated, and residues from those treatments are added to the current fuel load. The effects of surface fuel reduction treatments on the fuelbed are simulated, and the procedure is reiterated until the simulations yield a crown base height and a crown bulk density that meets the two target values.

Objective 1: Preventing Crown Ignition

Calculating the Target Crown Base Height.—Van Wagner's crown ignition equation is an extrapolation of heat transfer principles to the tree and stand scale. Under this equation, crown ignition is contingent on (1) the surface fireline intensity (rate of heat output at the fire's flaming front; directly related to flame length); (2) the stand's crown base height (height from the forest floor to the bottom-most live branches of tree crowns); and (3) the trees' foliar moisture content (percent moisture content of live foliage). In the equation, a taller crown base height requires a greater fireline intensity to ignite crown foliage, while greater foliar moisture retards ignition.

Van Wagner's equation defines a "critical surface fireline intensity" as the rate of heat release per unit length of fireline that is required to ignite a stand of specified crown base height and foliar moisture content. We adjusted the equation so that instead of calculating crown fire hazard for specific stand characteristics, we could calculate a crown base height above which crowns would fail to ignite for the fireline intensity expected during typical surface fire conditions. The equation to calculate the crown base height that resists the escalation of a surface fire to a crown fire (based on Van Wagner 1977) is:

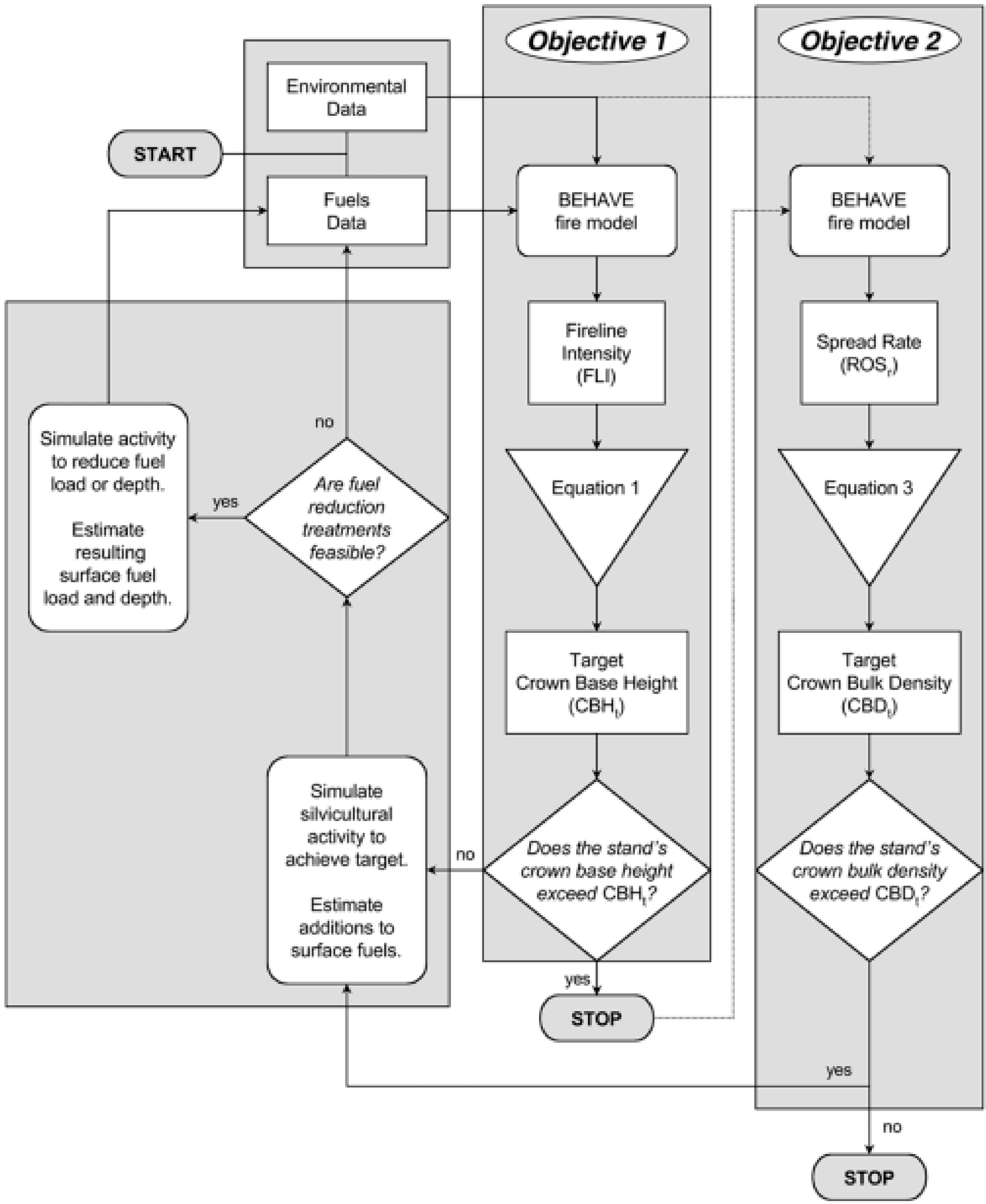

Figure 1. Flow of events for identifying a stand's target crown base height to resist crown fire initiation (Objective 1), and additional calculations to identify a target crown bulk density to resist crown fire spread (Objective 2).

$$CBH_t = [FLI^{(1/1.5)}] / [(0.010)(460 + 26 * FMC)] \quad (1)$$

where CBH_t (m) is the crown base height above which crown ignition is resisted for the predicted surface fireline intensity (FLI) (kW/m) and percent foliar moisture content (FMC) (oven-dry weight) under specified conditions. Equation (1) is the same as that used by NEXUS (Scott 1999) to calculate "critical crown base height." By predicting fireline intensity with BEHAVE, it is possible using this equation to quantify for any stand a value for crown base height that resists ignition. This height provides sufficient separation of crown and surface fuels to prevent surface fires from climbing into tree crowns.

Procedure Inputs.—Choosing appropriate values for the variables used in the procedure requires intelligent decision-making. For our study (Keyes 1996), summer foliar moisture content and fuel loads were estimated from published regional findings, and fireline intensity was predicted with BEHAVE using a set of values representing local site and weather variables. However, many sources of input data values exist. The following section details alternative sources and techniques that may be used by managers to produce sets of input data.

For our simulations, a foliar moisture content value of 90% was adopted to represent a scenario of extreme summer conditions. Foliar moisture content varies seasonally, a trend that is physiologically based and that remains relatively constant from year to year irrespective of variations in weather (Philpot and Mutch 1971). Lowest foliar moisture content typically occurs during late spring when fires are less common in the West. During the summer months when fires are most common, foliar moisture content generally ranges between 100% and 130%. We recommend setting foliar moisture content to 90% so that the predictions are conservative and the resulting stand structures are sufficient to tolerate a very low foliar moisture content.

In the Van Wagner model, however, the effect of foliar moisture content on crown ignition is minor relative to crown base height (as illustrated by Scott 1998). The relationship was supported by a laboratory study of conifer foliar combustion by Xanthopoulos and Wakimoto (1993), who found progressively less effect of foliar moisture content on ignition at lower levels and virtually no change in effect below approximately 100%. In Equation (1), the target crown base height is much more sensitive to surface fire intensity than foliar moisture content (Figure 2). Hence, in defining the target crown base height, emphasis should be on fireline intensity and the inputs associated with its prediction. A general estimate of foliar moisture content, based on local observations or published studies, is sufficient. If no information on foliar moisture content is available, a low default value of 90–100% is prudently conservative.

The other variable in Equation (1), fireline intensity (FLI), is predicted from surface fuel and environmental variables using the BEHAVE fire behavior model [for more details than those provided here, consult Rothermel (1983) and the BEHAVE user manuals (Andrews 1986, Burgan and Rothermel 1984)]. The first step in predicting surface fire

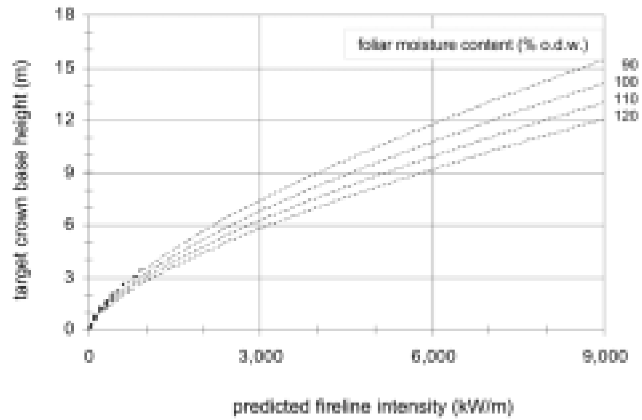

Figure 2. (Modeled after Alexander 1988.) The target crown base height defined by Equation (1) is a function of surface fireline intensity and foliar moisture content. This figure illustrates the relative sensitivity of the target height to fireline intensity for four levels of foliar moisture content (percent oven-dry weight).

behavior in BEHAVE involves selecting an appropriate fuel model to best represent surface fuel conditions. Anderson's (1982) visual and descriptive guide offers 13 stylized models that describe the general surface fuels associated with different vegetation types. Table 1 summarizes the models most useful for forest stands of different structures and fuel loads. Each model defines values for fuel depth and weight, surface-to-volume ratios, and other parameters required for surface fire behavior prediction. For our study (Keyes 1996), we used the long-needle pine model (9) for ponderosa pine (*Pinus ponderosa*) and model 8 for closed stands of shorter needled conifers, such as Douglas-fir (*Pseudotsuga menziesii*), Engelmann spruce (*Picea engelmannii*), western larch (*Larix occidentalis*), grand fir (*Abies grandis*), subalpine fir (*A. lasiocarpa*), western white pine (*Pinus monticola*), and lodgepole pine (*P. contorta*).

The fuel models are general and will not represent exactly the conditions at a specific site. Greater precision in the surface fire intensity prediction can be achieved by customizing the fuel models within BEHAVE to better represent site-specific conditions. We customized fuel depth and loading across the 1 hr, 10 hr, and 100 hr fuel classes. These fuel classes are based on the diameter of downed woody material and refer to the estimated time lag in fuel moisture content as ambient humidity changes. Stand fuel inventories, traditionally compiled by the line-intercept sampling method (Brown 1971), provide the best source for these values. Line-intercept sampling is labor-intensive and expensive, however, so photo guides can be used as a secondary option to characterize stand fuels. Such guides are used in the field to visually assess surface fuels in a manner that is inexpensive and reasonably accurate. Table 2 lists photo guides available for North American regions and conifer forest types. If an actual fuel assessment of the stand is not possible, then published fuel inventory summaries can be consulted for customizing the fuel model parameters. For example, Brown and See (1981) produced a regional summary of fuel loads by cover type for northern Rocky Mountain forests. This approach should be used only if it is not possible to characterize site

Table 1. Surface fuel models used for most conifer forest stand conditions. These models offer a useful starting point for surface fire behavior prediction in BEHAVE and may be modified for greater specificity to reflect fuel loads in individual stands (based on Anderson 1982).

Fuel model no.	Species types	Stand structure	Litter type
8 (Timber)	Short-needle conifers (e.g., PICO, ABIES, PSME)	Closed canopy (stem exclusion stage[1]). Little understory vegetation.	Light loads of litterfall primarily consisting of needles or leaves with some twigs.
9 (Timber)	Long-needle conifers (e.g., PIPO, PIPA)	Closed canopy (stem exclusion stage[1]). Little understory vegetation.	Same litter composition as No. 8, but heavier load of fine litter.
10 (Timber)	All conifers	Patchy overstory (understory reinitiation stage or old-growth stage[1]). Understory vegetation present.	Deeper fuel bed with natural accumulation of litter and downed wood from over-maturity or disturbance such as windthrow or insect outbreak.
11 (Slash)	All conifers	Open canopy following silvicultural operation. Little understory vegetation.	Large loads characterized by medium-sized debris resulting from thinning or small partial cuts.
12 (Slash)	All conifers	Open canopy or scattered overstory trees following silvicultural operation. Little understory vegetation.	High slash and large loads with large-diameter debris due to heavy thinning or regeneration harvest.

[1] Stand development stage as described by Oliver and Larson 1996.

fuels with sampling or photo guides. If such regional fuel estimates are used, values that exceed the published average should be adopted. This strategy produces silvicultural targets that accommodate a greater range of surface fuel loads, which tend to be highly variable on both a within-stand and between-stand basis.

In addition to the surface fuel complex, it is necessary to define several site and weather parameters that influence surface fire behavior. These include slope, windspeed, and fuel moisture content. An estimate of slope is usually available from typical stand inventory databases. If there is substantial variation in slope within a stand, a value representing the higher end of the range should be used. Unlike slope, which is a fixed attribute, windspeed and fuel moisture vary with season and year and hence are more difficult to estimate. Values for these parameters should be based on worst-case fire weather scenarios—the worst conditions that are reasonably expected for a particular site. For windspeed, historical records from local weather stations are most useful. If historic weather data are not available, another option is to

Table 2. Photo guides for characterizing surface fuel loads in North American conifer forests.

Region	Species cover types[1]	Fuel[2]	Reference
Pacific Northwest	PIEN-ABLA, mixed conifer, PSME-TSHE, PSME-hardwood, PICO, PIPO, JUOC	N	Maxwell and Ward 1980
	PSME-TSHE, PSME-hardwood	S	Maxwell and Ward 1976a
	PIPO, PICO-mixed conifer, PICO	S	Maxwell and Ward 1976b
	PSME - TSHE, TSHE - PISI	S	Ottmar and Hardy 1989
	PSME-TSHE	S	Ottmar et al. 1990
Southern Cascades / Northern Sierra Nevada	TSME, ABMA, ABCO, mixed conifer-fir, mixed conifer-pine, PICO, PIPO	N	Blonski and Schramel 1981
Sierra Nevada	Mixed conifer, true fir	S	Maxwell and Ward 1979
	SEGI, mixed conifer	N/S/F	Weise et al. 1997
Southwest	ABCO, mixed conifer, PICO, PIPO, JUOC	N/S	USDA-FS SW Region 1996
Idaho / Montana	TSHE, THPL, ABGR	S	Koski and Fischer 1979
	PIEN-ESAF, PICO	N	Fischer 1981a
	THPL, TSHE, THPL-TSHE, ABGR-LAOC-PSME	N	Fischer 1981b
	PSME, LAOC-PSME, PIPO-LAOC-PSME, PIPO	N	Fischer 1981c
Black Hills	PIGL, PIPO	N/S	USDA-FS RM Region 1990
Upper Midwest	PIBA	S	Blank 1982
Southern Appalachians	Mixed pine-hardwoods	S/F	Sanders and Van Lear 1988
Southeast	PITA, PIPA	N/F	Scholl and Waldrop 1999
	Mixed pine	H/F	Wade et al. 1993

[1] Four-letter codes consist of first two letters each of scientific genus and species names.
[2] Fuel type: N = natural, S = harvest or thinning slash, F = post-fire, H = post-hurricane.

select a windspeed value representing extreme conditions, such as 80 km/hr. In BEHAVE, ambient windspeed must be converted to midflame windspeed by adjusting down for the moderating effects of vegetation. The multiplier is 0.3 for stands that have a patchy canopy or occur at exposed sites; the multiplier at protected sites is 0.2 for open-canopy stands and 0.1 for closed-canopy stands (Rothermel 1983). For more discussion on selecting an appropriate windspeed and adjustment factor, consult Rothermel (1983) or Albini and Baughman (1979).

Suitable values for woody fuel moisture contents may be based on hazard indexes. For the 1, 10, and 100 hr fuel categories, we used extreme moisture contents of 4, 5, and 5%, respectively, to represent a scenario of "wildfire" conditions. These values were suggested by the Fire Effects Project of the Missoula Fire Sciences Laboratory, which has assembled groups of values for fire weather scenarios (E.D. Reinhardt, pers. comm.). Rothermel (1983) discusses more extensively the selection of fuel moisture contents for fire behavior prediction.

Objective 2: Crown Fire Cessation

Once the target crown base height is identified for preventing crown ignition, structures can also be prescribed to make the stand resistant to crown fires spreading from adjacent stands. The procedure for this objective continues the procedure used to define the target crown base height.

Calculating the Target Crown Bulk Density.—Crown bulk density is a parameter that describes density of crown fuels or the mass of foliage and twigs within the volume of space occupied by tree crowns. Van Wagner's (1977) model defines a critical crown fire spread rate that is required for crown fires to be sustained in a stand of a given crown bulk density. That equation can be reversed to define a critical crown bulk density for a predicted spread rate, as follows:

$$CBD_t = (3.0) / (ROS_c) \qquad (2)$$

where CBD_t is the crown bulk density (kg/m^3) below which crown fire spread is resisted for the crown fire spread rate (ROS_c) (m/min) estimated to occur under specified conditions.

Predicting a stand's anticipated crown fire spread rate is a much less precise exercise than predicting its surface fire spread rate. Using data from eight documented crown fire runs, Rothermel (1991) identified a correlation rate of 3.34 that related empirical crown fire spread rates to the surface fire spread rates predicted for those stands by the BEHAVE surface fire behavior model using Fuel Model 10 (Anderson 1982) and a wind reduction factor of 0.4 (Rothermel 1983). Users must perform a second BEHAVE run to produce an estimate of surface fire rate of spread (ROS_r)—using Fuel Model 10, a wind reduction factor of 0.4, and the site-based estimates for slope, windspeed, and fuel moisture values that were used in the Objective 1 procedure. The target crown bulk density (CBD_t) is calculated by Equation (3):

$$CBD_t = (3.0) / ((3.34)(ROS_r)) \qquad (3)$$

where ROS_r (m/min) is the spread rate of a surface fire predicted by BEHAVE for Fuel Model 10, a midflame windspeed reduction factor of 0.4, and the same environmental conditions used in Equation (1) for calculating CBH_t.

To summarize, if a stand's crown base exceeds the Equation (1) height but its crown bulk density is less than the density identified in Equation (3), the stand is resistant to crown ignition but not to the spread of crown fires. A stand with crown base greater than the Equation (1) CBH_t and a crown bulk density less than the Equation (3) CBD_t is resistant to crown ignition by surface fires and to spreading crown fires. One of the advantages of this procedure is that it enables experimentation with the input variables, and we recommend carrying it out several times with different combinations of input values. In this way the potential fire behaviors that might be expected at a site are better understood, and silvicultural targets for the stand can be more judiciously determined.

Discussion

Because a stand's susceptibility to crown fire is a function of both the surface fuel complex and crown structure, several options for proactive management of crown fire hazard are available. Surface fuel management can reduce future surface fire behavior and hence can lower the crown base height that is necessary to resist crown ignition. Alternatively, practices can be conducted to raise the crown base above the target height for existing surface fuels or to remove some stems to decrease crown bulk density below the target. Often these practices are compatible with other forest objectives and are easily integrated into multiple-resource management plans. Where possible, the best hazard-abating strategy is a combination of the two approaches.

Manipulating Surface Fuels

Growing consideration by many forest managers is given to the use of prescribed fire as a means of curtailing crown fire activity by consuming the volumes of fuel that have accumulated during past decades of fire suppression. Prescribed burning partially consumes existing surface fuels and reduces the expected intensity of future fires and therefore can be used to reduce the target crown base height below the existing crown base height. Prescribed burning can also raise the stand's crown base above the target height by crown scorch. In locations of high hazard or strong public resistance to prescribed burning, it is instead possible to reduce anticipated surface fire behavior by adjusting the density, rather than the mass, of the existing fuel complex. A sensitive fuels parameter used by the BEHAVE model is fuelbed depth, and surface fireline intensity is generally lessened when the volume that fuel occupies is smaller. Mechanically compacting and lowering fuels reduces the fuelbed depth and also expedites the decomposition of fuels.

Many stands have experienced fire suppression for so long that dead and live surface fuels have accumulated beyond levels that are safe for controlled burning. Such stands often require some silvicultural treatment as a prerequisite to initiating a prescribed burning program. This is especially true in ecosystems that were traditionally maintained by frequent fires, where fire suppression has resulted in fuel loadings that are substantially above historic levels. In the interior West, for example, safe burning in many ponderosa pine stands is not possible without some initial treatments that first modify the stand's crown structure (Mutch et al. 1993, Covington and Moore 1994).

Manipulating Stand Structure

Silvicultural treatments that alter crown structure can be used in conjunction with surface fuel reduction treatments or they may be used alone. No single treatment can be prescribed for all situations. With the variety of site conditions and management objectives that can exist, a combination of pruning and thinning should be tailored to the specific conditions and objectives of each individual stand.

For raising the stand's crown base height beyond the target height, pruning lower dead and live branches yields the most direct and effective impact. By removing all branches up to the target height, pruning ensures that the residual stand's crown base height is uniformly above the target, while minimizing the addition of surface fuels. This method is particularly desirable for younger stands, where the positive effects of pruning on bole quality will be more greatly expressed. A more traditional method is thinning from below, an approach that is more efficient than pruning when the target crown base height is very high. By a process of attrition, light thinning that removes smaller trees—the suppressed and intermediate trees with lower crown base heights—raises the stand's crown base height to that of the residual trees. But this approach is ineffective for stands with poor height stratification, a condition typical of many even-aged monospecific stands.

Heavy thinning is a reasonable approach in stands that are to be treated as green firebreaks (Agee et al. 2000). For those stands, thinning can be used to reduce canopy fuels in order to create a structure that is resistant to crown fire spread. Practical examples of stands treated in this way have been reported to disrupt rolling crown fires. Agee (1996), for example, analyzed seven stands that had been thinned and subsequently exposed to the spread of crown fire from an adjacent stand. Empirical data from those fires showed that crown fires were not sustained in stands thinned to crown bulk densities below approximately 0.10 kg/m^3.

For many stands, however, the heavy thinning approach is not practical, as the low stand densities required to achieve the crown bulk density defined by Equation (3) can be incompatible with other forest management objectives except those that call for less-than-full stocking. Figure 3 offers a rough illustration of this point. Using estimates of crown bulk density provided by Agee (1996), Figure 3 shows the relationship between crown bulk density and relative density, or percent of maximum stand density index (SDI) (Reineke 1933, Drew and Flewelling 1979), for unstratified, even-aged stands of grand fir, Douglas-fir, and ponderosa pine in the northern Rockies. The trendlines for each species were fitted to estimates of crown bulk density calculated for varying structures (mean diameter ranging from 3 to 40 in. dbh; trees/ac ranging from 20 to 1300). SDI coefficients and maximum values were based on those summarized by Cochran et al. (1994) for northeastern Oregon.

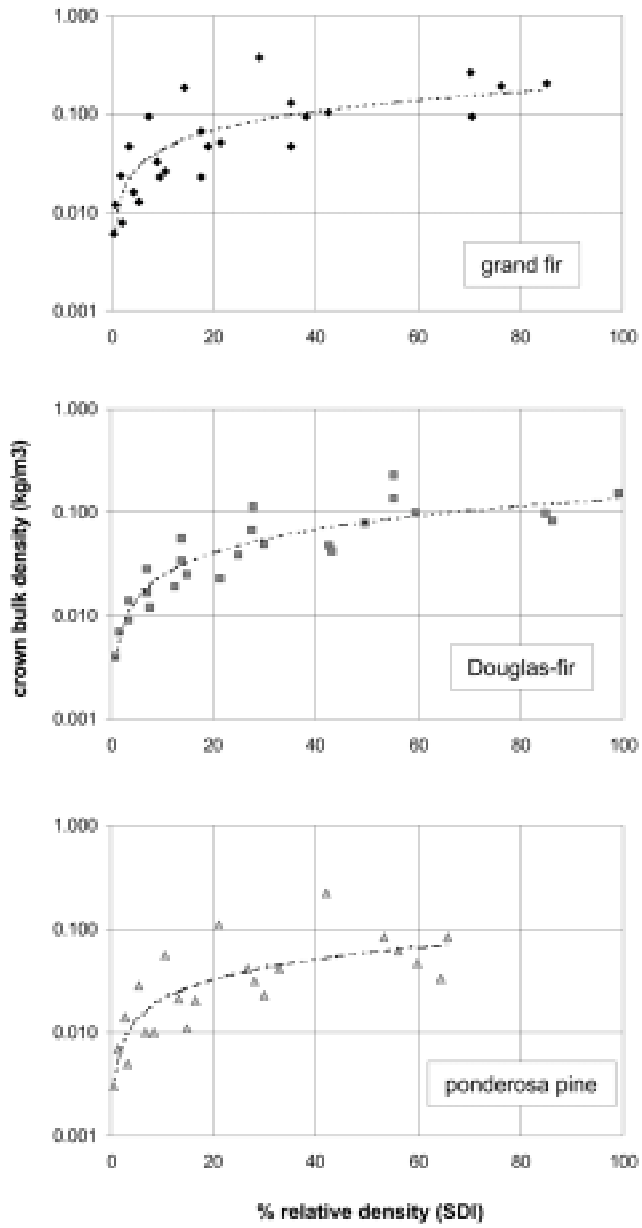

Figure 3. Relationship of crown bulk density to relative density (percent of maximum SDI) for simulated stands of three western conifers. Curves are fitted to crown bulk density calculations for different stand structures of unstratified, even-aged stands of grand fir ($y = 0.0097x^{0.6538}$; $r^2 = 0.67$), Douglas-fir ($y = 0.0043x^{0.7506}$; $r^2 = 0.84$), and ponderosa pine ($y = 0.0046x^{0.6528}$; $r^2 = 0.64$).

Under the Van Wagner model, crown fire spread is nearly impossible below a crown bulk density of 0.05 kg/m^3 (as illustrated by Alexander 1988). Based on the relationships in Figure 3, in order to achieve 0.05 kg/m^3 CBD, stands of grand fir must be kept at a relative density of about 12%, Douglas-fir at about 26%, and ponderosa pine at about 38%. To maintain them below the empirical crown bulk density threshold of 0.10 kg/m^3 observed by Agee (1996), relative density of grand fir stands must be kept below about 35% and Douglas-fir below about 66%; ponderosa pine remains below the threshold even at maximum density. Because the relative density range for optimum stand growth is 40 to 55% (Drew and Flewelling 1979), stands thinned to remain below 40%

relative density will always be understocked—especially during the years immediately after thinning events. This simple example suggests that the low requisite relative crown bulk densities will result in a reduction in stand growth for some species.

Much more work is needed to provide good models relating crown bulk density to other measures of stand density. Crown bulk density is a parameter that is difficult to convey to forest workers and hence is a poor silvicultural target. It remains necessary to relate crown bulk density to more common and more useful stand density measures such as those described by Curtis (1970). At the USDA Forest Service's Fire Sciences Lab, researchers are conducting a project to correlate crown fuels with standard forest inventory measurements. That project will likely enable crown bulk density to be predicted from stand-level, size-independent measures of relative density such as SDI. Such a measure would provide a practical structural target with which forest managers and workers are readily familiar.

If compatible with other management objectives, stands should be maintained at or near, rather than substantially below, the calculated density target. One reason is that the higher density encourages self-pruning and rapid crown recession, thus constituting a natural method of sustained crown fuel control. A second reason is that overstory density is strongly related to understory development. The review of stand development patterns by Oliver and Larson (1996) provides many indications that silvicultural practices that substantially reduce canopy cover will facilitate shrub release and the initiation of secondary tree cohorts. Such practices promote ladder fuels and work counter to the long-term objective of preventing crown fires. Those ladder fuels can be held at bay with a regime of periodic stand entries to maintain open understories, but that approach demands an obligation to frequent and expensive understory-burning or brush-cutting. If institutional commitment to that type of regime is lacking, heavy thinning is not advised.

The litter accumulating from pruning and thinning can substantially inflate surface fuels, so it is necessary to estimate their impact on the fuelbed. Stephens' (1998) modeling study showed that if the slash resulting from silvicultural practices is not burned or removed, posttreatment fire intensity could increase substantially, thus necessitating a higher target crown base height. This increased fire danger may be temporary, however. Fuel decay curves, such as those constructed by Carlton and Pickford (1982) and Christiansen and Pickford (1991) for thinning slash, are useful in estimating the duration of the inflated posttreatment fuelbed.

A silvicultural approach to reducing crown fire hazard may not be compatible with all forest objectives. For example, habitat management for a wildlife species that requires a complex, multilayered canopy will not be compatible with a low-thinning regime to reduce ladder fuels. However, the silvicultural practices described here—pruning and thinning—are consistent with stand management objectives that emphasize stand growth, wood quality, and individual tree vigor for pest and disease resistance. Although silvicultural practices can increase stand resistance to crown fires by manipulating stand structure, under extreme wildfire conditions these preventative measures can be rendered ineffective. Furthermore, even surface fires can have destructive effects if unmanaged surface fuels are allowed to rise to excessively high levels. A severe surface fire may cause crown, root, or cambium injury—and substantial tree mortality, even without crowning (Ryan and Reinhardt 1988).

Conclusion

Stand structure plays a critical role in crown fire susceptibility. Forest managers can exploit this relationship with silvicultural practices that, by altering canopy structure, have the potential to prevent surface fires from developing into crown fires. Using existing models of surface fire and crown fire behavior, it is possible to identify crown base heights and crown bulk densities as quantitative targets for posttreatment stand structure. When these targets are combined with an understanding of forest stand dynamics, the groundwork is laid for prescribing specific silvicultural practices for individual stands that yield a sustained reduction in crown fire potential at the stand level.

For the objective of preventing crown ignition, silvicultural practices should attempt to raise the stand's crown base height above its target height while not promoting understory development. Pruning and low thinning are most effective at achieving this goal. For the objective of causing crown fire cessation, heavier thinning can reduce crown bulk density below the target level. Because heavy thinning counterproductively facilitates understory reinitiation and the subsequent development of ladder fuels, a followup regime of regular low-intensity burning or brush-cutting may be necessary to maintain an open understory and sustain crown fire resistance.

As the practice of fire management continues to evolve from an approach of reactive suppression to one of proactive prevention, silvicultural treatments can play a valuable role in reducing the susceptibility of stands to crown fires. The method outlined here provides forest managers with a tool for determining quantitative target stand structures for this objective. However, the process of combining silvicultural and fuel management practices in a regime that best fits site conditions and objectives remains an artful endeavor. No manipulative effort can guarantee a fire-proof condition in any stand, but the methods and practices described here provide the best available means of shaping stands that are resistant to crown fires.

Literature Cited

Agee, J.K. 1996. The influence of forest structure on fire behavior. P. 52–68 *in* Proc., 17th Forest Vegetation Management Conf., S.L. Cooper (comp.). Univ. of California, Shasta County Coop. Ext., Redding, CA.

Agee, J.K., B. Bahro, M.A. Finney, P.N. Omi, D.B. Sapsis, C.N. Skinner, J.W. van Wagtendonk, and C.P. Weatherspoon. 2000. The use of shaded firebreaks in landscape fire management. For. Ecol. Manage. 127:55–66.

Albini, F.A., and R.G. Baughman. 1979. Estimating windspeeds for predicting wildland fire behavior. USDA For. Serv. INT-RP-221. 12 p.

Alexander, M.E. 1988. Help with making crown fire hazard assessments. P. 147–156 in Protecting People and Homes from Wildfire in the Interior West: Proc. of the symp. and workshop, Fischer, W.C., and S.F. Arno (comps.). USDA For. Serv. INT-GTR-251.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. USDA For. Serv. INT-GTR-122. 22 p.

Andrews, P.L. 1986. BEHAVE: Fire behavior prediction and fuel modeling system—burn subsystem, Part 1. USDA For. Serv. INT-GTR-194. 130 p.

Andrews, P.L., and C.D. Bevins. 1999. BEHAVE fire modeling system: Redesign and expansion. Fire Manage. Notes 59(2):16–19.

Blank, R.W. 1982. Stereo photos for evaluating jack pine slash fuels. USDA For. Serv. NC-GTR-77. 23 p.

Blonski, K.S., and J.L. Schramel. 1981. Photo series for quantifying natural forest residues: Southern Cascades, northern Sierra Nevada. USDA For. Serv. PSW-GTR-56. 145 p.

Brown, J.K. 1971. A planar intercept method for sampling fuel volume and surface area. For. Sci. 17(1):96–102.

Brown, J.K., and T.E. See. 1981. Downed dead woody fuel and biomass in the northern Rocky Mountains. USDA For. Serv. INT-GTR-117. 48 p.

Burgan, R.E., and R.C. Rothermel. 1984. BEHAVE: fire behavior prediction and fuel modeling system—Fuel subsystem. USDA For. Serv. INT-GTR-167. 126 p.

Carlton, D.W., and S.G. Pickford. 1982. Fuelbed changes with aging of slash from ponderosa pine thinnings. J. For. 80(2):91–93, 107.

Christiansen, E.C., and S.G. Pickford. 1991. Natural abatement of fire hazard in Douglas-fir blowdown and thinning fuelbeds. Northwest Sci. 65(4):141–148.

Cochran, P.H., J.M. Geist, D.L. Clemens, R.R. Clausnitzer, and D.C. Powell. 1994. Suggested stocking levels for forest stands in northeastern Oregon and southeastern Washington. USDA For. Serv. PNW-RN-513. 20 p.

Covington, W.W., and M.M. Moore. 1994. Southwestern ponderosa pine forest structure: Changes since Euro-American settlement. J. For. 92(1):39–47.

Curtis, R.O. 1970. Stand density measures: An interpretation. For. Sci. 16:403–414.

Drew, T.J., and J.W. Flewelling. 1979. Stand density management: An alternative approach and its application to Douglas-fir plantations. For. Sci. 25:518–532.

Finney, M.A. 1998. FARSITE: Fire Area Simulator—Model development and evaluation. USDA For. Serv. RMRS-RP-4. 47 p.

Fischer, W.C. 1981a. Photo guide for appraising downed woody fuels in Montana forests: lodgepole pine, and Engelmann spruce—subalpine fir cover types. USDA For. Serv. INT-GTR-98. 143 p.

Fischer, W.C. 1981b. Photo guide for appraising downed woody fuels in Montana forests: Grand fir–larch–Douglas-fir, western hemlock, western hemlock–western redcedar, and western redcedar cover types. USDA For. Serv. INT-GTR-96. 53 p.

Fischer, W.C. 1981c. Photo guide for appraising downed woody fuels in Montana forests: Interior ponderosa pine, ponderosa pine–larch–Douglas-fir, and interior Douglas-fir cover types. USDA For. Serv. INT-GTR-97. 133 p.

Graham, R.T., A.E. Harvey, T.B. Jain, and J.R. Tonn. 1999. The effects of thinning and similar stand treatments on fire behavior in western forests. USDA For. Serv. PNW-GTR-463. 27 p.

Johnson, K.N., J. Sessions, J. Franklin, and J. Gabriel. 1998. Integrating wildfire into strategic planning for Sierra Nevada forests. J. For. 96(1):42–49.

Keyes, C.R. 1996. Stand Structures and silvicultural strategies to prevent crown fires in Northern Rocky Mountain forests. M.S. thesis, Univ. of Montana, Missoula. 116 p.

Koski, W.H., and W.C. Fischer. 1979. Photo series for appraising thinning slash in north Idaho: Western hemlock, grand fir, and western redcedar timber types. USDA For. Serv. INT-GTR-46. 50 p.

Maxwell, W.G., and F.R. Ward. 1976a. Photo series for quantifying forest residues in the coastal Douglas-fir–hemlock type, coastal Douglas-fir–hardwood type. USDA For. Serv. PNW-GTR-51. 103 p.

Maxwell, W.G., and F.R. Ward. 1976b. Photo series for quantifying forest residues in the ponderosa pine type, ponderosa pine and associated species type, lodgepole pine type. USDA For. Serv. PNW-GTR-52. 73 p.

Maxwell, W.G., and F.R. Ward. 1979. Photo series for quantifying forest residues in the Sierra mixed conifer type, Sierra true fir type. USDA For. Serv. PNW-GTR-95. 79 p.

Maxwell, W.G., and F.R. Ward. 1980. Photo series for quantifying forest residues in common vegetation types of the Pacific Northwest. USDA For. Serv. PNW-GTR-105. 230 p.

Mutch, R.W., S.F. Arno, J.K. Brown, C.E. Carlson, R.D. Ottmar, and J.L. Peterson. 1993. Forest health in the Blue Mountains: A management strategy for fire-adapted ecosystems. USDA For. Serv. PNW-GTR-310. 14 p.

O'Hara, K.L., R.S. Seymour, S.D. Tesch, and J.M. Guldin. 1994. Silviculture and our changing profession. J. For. 92(1):8–13.

Oliver, C.D., and B.C. Larson. 1996. Forest stand dynamics. Update Edition. Wiley, New York. 520 p.

Ottmar, R.D., and C.C. Hardy. 1989. Stereo photo series for quantifying forest residues in coastal Oregon forests: Second-growth Douglas-fir–western hemlock type, western hemlock–Sitka spruce type, and red alder type. USDA For. Serv. PNW-GTR-231. 67 p.

Ottmar, R.D., C.C. Hardy, and R.E. Vihnanek. 1990. Stereo photo series for quantifying forest residues in the Douglas-fir–hemlock type of the Willamette National Forest. USDA For. Serv. PNW-GTR-258. 63 p.

Philpot, C.W., and R.W. Mutch. 1971. The seasonal trends in moisture content, ether extractives, and energy of ponderosa pine and Douglas-fir needles. USDA For. Serv. INT-RP-102. 21 p.

Reineke, L.H. 1933. Perfecting a stand density index for even-aged forests. J. Agric. Res. 46:627–638.

Rothermel, R.C. 1983. How to predict the spread and intensity of forest and range fires. USDA For. Serv. INT-RP-115. 161 p.

Rothermel, R.C. 1991. Predicting the behavior and size of crown fires in the northern Rocky Mountains. USDA For. Serv. INT-RP-438. 46 p.

Ryan, K.C., and E.D. Reinhardt. 1988. Predicting postfire mortality of seven western conifers. Can. J. For. Res. 18:1291–1297.

Sanders, B.M., and D.H. Van Lear. 1988. Photos for estimating residue loadings before and after burning in Southern Appalachian mixed pine–hardwood clearcuts. USDA For. Serv. SE-GTR-49. 21 p.

Scholl, E.R., and T.A. Waldrop. 1999. Photos for estimating fuel loadings before and after prescribed burning in the upper coastal plain of the Southeast. USDA For. Serv. SRS-GTR-26. 25 p.

Scott, J.H. 1999. NEXUS: A system for assessing crown fire hazard. Fire Manage. Notes 59(2):20–24.

Scott, J.H. 1998. Sensitivity analysis of a method for assessing crown fire hazard in the northern Rocky Mountains, USA. P. 2517–2532 in Proc., Third Internat. Conf. on For. Fire Res. and Fourteenth Conf. on Fire and For. Meteorol., Luso, Portugal.

Stephens, S.L. 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in Sierra Nevada mixed-conifer forests. For. Ecol. Manage 105:21–35.

USDA Forest Service Rocky Mountain Region. 1990. Photo series for quantifying forest residues in the Black Hills: Ponderosa pine type, spruce type. USDA For. Serv. Rocky Mountain Region, Custer, SD. 80 p.

USDA Forest Service Southwestern Region. 1996. Photo series for quantifying forest residues in the Southwestern Region. USDA For. Serv. Southwestern Region, Albuquerque, NM. 227 p.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. 7:23–34.

Van Wagner, C.E. 1989. Prediction of crown fire behavior in conifer stands. P. 207-212 in Proc., Tenth Conf. on Fire and For. Meteorol., Ottawa, Canada.

Van Wagner, C.E. 1993. Prediction of crown fire behavior in two stands of jack pine. Can. J. For. Res. 23:442–449.

Wade, D.D., J.K. Forbus, and J.M. Saveland. 1993. Photo series for estimating post-hurricane residues and fire behavior in southern pine. USDA For. Serv. SE-GTR-82. 19 p.

Weise, D.R., A. Gelobter, S.M. Haase, and S.S. Sackett. 1997. Photo series for quantifying fuels and assessing fire risk in giant sequoia groves. USDA For. Serv. PSW-GTR-163. 49 p.

Wilson, J.S., and P.J. Baker. 1998. Mitigating fire risk to late-successional forest reserves on the east slope of the Washington Cascade Range, USA. For. Ecol. Manage. 110(1/3):59–75.

Xanthopoulos, G., and R.H. Wakimoto. 1993. A time to ignition–temperature–moisture relationship for branches of three western conifers. Can. J. For. Res. 23:253–258.