The Influence of Forest Structure on Fire Behavior

James K. Agee
College of Forest Resources, University of Washington, Seattle, Washington

Western forests have burned for millennia with a wide range of frequencies, intensities, and extents. Some forests have fire-resistant trees and others do not. The combination of the physical characters of the fires themselves, together with the adaptations of the tree species to fire, have resulted in forest types that can be classified into natural fire regimes (Agee 1993). Three broad categories of fire severity may be defined, based on the physical characters of fire and the fire adaptations of vegetation: low, mixed or moderate, and high. A low severity fire regime is one where the effect of the typical historical fire is benign. Fires are frequent (often <20 years), of low intensity, and the ecosystems have dominant vegetation well-adapted to survive fire. At the other end of the spectrum is the high severity fire regime, where fires are usually infrequent (often >100 years) but may be of high intensity; most of the vegetation is at least top-killed. In the middle is the mixed or moderate severity fire regime, where fires are of intermediate frequency (25-100 years), range from low to high intensity, and have vegetation with a wide range of adaptations.

Fire behavior is a function of fuels, weather, and topography, the "fire behavior triangle". All three legs of the triangle have significant effects on fire behavior, but the fuels leg is most related to forest structure, and is the only controllable factor of the three. There are also interactions between these factors which will be discussed later. Forest structure consists of flammable biomass, whether it is live or dead. Forest structure can be interpreted as three-dimensional patches of fuel, with differing amounts, size classes, arrangements, and flammability. Some fuels, such as large tree boles, rarely are consumed by fire, while others, such as surface needle litter, are partially to wholly consumed in every fire. Others, such as leaves in the tree crowns, are inconsequential in surface fires but a major source of energy in crown fires. Forest structure affects fire behavior, and fire behavior in turn affects forest structure.

It is important to separate fireline intensity from fire severity. Intensity is the energy release rate per unit length of fireline, and is a physical parameter that can be related to flame length. It can be determined from the product of biomass consumption (energy) and rate of spread of the fire. Fire severity is an ecological parameter that measures, albeit somewhat loosely, the effects of the fire. Two fires of the same fireline intensity can have quite different effects between an old-growth mixed-conifer forest and a young plantation of similar species because the smaller plantation trees will be more easily scorched and have thinner bark. The fire in the old-growth may be of low severity while the plantation fire is of high severity. We generally are more interested in fire severity, but must approach severity first by estimating fireline intensity and then using models such as FOFEM (Keane et al. 1995) to predict tree mortality from fireline intensity.

We have traditionally evaluated fire and forest structure at the stand level, and are beginning to utilize landscape-level tools to study larger-scale issues. At the stand level, there are horizontal and vertical components to the fuel matrix, and at the landscape level, myriad patches of forest each with a unique fuel structure that may carry fire along the surface or through the tree crowns. The following discussion is organized around surface and crown fire behavior rather than all of the combinations of fuel structures that could be imagined. The intent is to summarize some of the structural characteristics of forests that lead to manageable fire behavior, or "fire-safe" forests. "Fire-safe" forests are not fireproof, but will have:

- Surface fuel conditions that limit surface fireline intensity;
- Forest stands that are comprised of fire-tolerant trees, described in terms of species, sizes, and structures.
- A low probability that crown fires will either initiate or spread through the forest;

These characters are not independent of one another, but it is possible to define a matrix of acceptable conditions at the stand level that constitute a fire-safe forest. One important caveat must be emphasized here: not every parcel of landscape can or need be treated to make it "fire-safe". There are competing objectives associated with biodiversity and fish and wildlife habitat that suggest landscape units or patches be prioritized for treatment, as not all can or should be treated. Some high-elevation forests always burned with crown fire and probably always will, so that attempts to make such forests "fire-safe" are somewhat futile. Management objectives will sometimes favor maintaining late-successional or old-growth forests, and while those patches may not be treated, surrounding forest patches may well need fuels treatment to help protect the late-successional patches.

MANAGING SURFACE FUELS TO LIMIT FIRELINE INTENSITY

Surface fuel management can limit fireline intensity and lower potential fire severity. It can also increase fireline intensity or increase fire severity, depending on which fuels are managed and how the operation is conducted. Forest entry for fuels management purposes usually results in altered microclimates, and although less total biomass may be present, more of it may be in the dead fuel category and left lying on the forest floor. The management of surface fuels so that potential fireline intensity remains below some critical level (discussed later) can be accomplished through several strategies and techniques. Among the common strategies are fuel removal by thinning trees, adjusting fuel arrangement to produce a less flammable fuelbed, and "introducing" live understory vegetation to raise average moisture content of surface fuels.

The various surface fuel categories interact with one another to influence fireline intensity. Although more litter and fine branch fuel on the forest floor usually result in higher intensities, that is not always the case. If additional fuels are packed tightly (low fuelbed porosity), they may result in lower intensities. Larger fuels (>3 inches) are ignored in fire spread models as they do not usually affect the spread of the fire (unless decomposed

[Rothermel 1991]). They may, however, result in higher energy releases over longer periods of time and have significant effects on fire severity.

The effect of herb and shrub fuels on fireline intensity is not simply predicted. First of all, more herb and shrub fuels usually imply more open conditions, which are associated with lower relative humidities and higher windspeeds. Dead fuels may be drier, and the rate of spread may be higher, because of the altered microclimate from more closed canopy forest with less understory. Secondly, shrub fuels vary significantly in heat content. Waxy or oily shrubs like snowbrush (*Ceanothus velutinus*) or bear clover (*Chamaebatia foliolosa*) burn quite hot; others have lower heat contents. Perhaps most important, though, is the effect of the live fuels on moisture content of the fuelbed. Fine dead fuels will often be at moisture contents of 10% or less, while foliar moisture of live understory vegetation will be at 100% or higher. In the dry eastern Cascades in the wetter than normal summer of 1995, average shrub moisture content in September was 125%, and grasses were at 93% (J.K. Agee, unpublished data). These fuels will have a dampening effect on fire behavior. However, if the grass component is annual, or perennial grasses and forbs cure, the fine dead fuel can increase fireline intensity. Post-fire analyses of fire damage to plantation trees after the 1987 fires in the Hayfork District of the Shasta-Trinity National Forest (Weatherspoon and Skinner 1995) showed a positive relationship between grass cover and damage and a negative relationship between forb cover and damage (Figure 1), most likely because grasses were cured and forbs were not.

Management of forest structure to reduce fuels can be done manually, mechanically, or through prescribed burning. In harvesting operations, one potential removal technique is

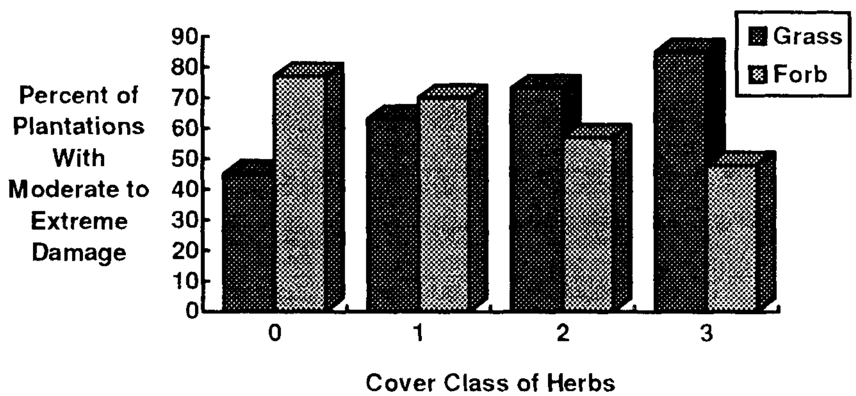

Figure 1. Fire damage to mixed conifer plantation in the 1987 fires was worse when grass cover was higher but less when forb cover was higher (Weatherspoon and Skinner 1995). Moderate to extreme damage includes more than 10% of trees with >50% scorch to >50% trees with crowns consumed. Cover classes are 0 = not present; 1 = 1-20%; 2 = 21-50%; and 3 = 51-100%.

whole-tree yarding, with trees cut by feller-bunchers hauled to landings with grapple skidders, and delimbing occurring at landings. Debris is chipped or burned there. Other fuel removal strategies may include manual tree cutting and pile burning with sites scattered through the woods, or prescribed burning under moist conditions. These strategies will generally result in less fuel and more moderate fire behavior after treatment. Adjusting fuel arrangement may be another strategy to produce a less flammable fuelbed. In thinning operations with harvester/forwarder equipment, limbing is done in the woods directly ahead of the forwarder, which then rolls over the limbs, reducing soil compaction effects of the equipment and making a more compact fuelbed. A third strategy is often the result of thinning operations: recruitment of understory vegetation, both shrubs and herbs, that maintain high moisture content and provide a dampening effect on fire behavior.

Such treatment will not always reduce potential fire behavior or fire severity. If the thinning is a selective or crown thinning that removes larger trees, the average fire resistance of the stand will decrease because the residuals have a smaller average diameter and height, and potential fire severity will be higher. Conversely, a low thinning will reduce potential fire severity as average residual tree size will increase. Potential fire behavior is likely to change after treatment (Table 1, Figure 2). An unthinned stand of ponderosa pine with fire behavior characteristics of NFFL Model 9 (Burgan and Rothermel 1984) will have flame lengths of 3-5 feet under moderate fire weather. A stand entry for thinning could increase potential fire behavior by adding fuel loading and fuel depth. The thinning treatment if fuels were removed (such as whole tree yarding) could reduce fire behavior to Model 9 values, or could increase fuel loading even beyond the example shown (a lop and scatter approach, for example). If the stand is thinned heavily enough to allow herb and shrub understory to establish, and the herbs are not cured, this addition of live fuels, even with the increased dead fuel loading, reduces fire behavior below that of Model 9. Generally, shrub foliar moisture will remain high and herb moisture will decline over the summer, particularly if the herbs are annuals.

Prescribed burning has been found to reduce subsequent wildfire damage through its effects on surface fuel loading reduction and on mortality of understory trees and shrubs that might carry fire into the canopy trees (Helms 1979, Buckley 1992). In most of our western United States forests, prescribed fire has not been applied widely enough to have much effect on wildfire behavior at a landscape scale.

MANAGING CROWN FUELS TO PREVENT CROWN FIRE BEHAVIOR

The development and maintenance of a forest relatively free of crown fire potential is primarily dependent on management of the structure of crown fuels. Topography and weather, the other "legs" of the "fire behavior triangle", are either fixed or uncontrollable. The regulation of crown fire potential can be approached from two complementary perspectives:

- Prevention of conditions that initiate crown fire
- Prevention of conditions that allow spread of crown fire

If either or both of these criteria can be achieved within a stand, then the chance of crown fire, and/or blowup fire behavior, is very low. If they can be achieved across the entire landscape, the possibilities of blowups are essentially eliminated. In the following analysis, these conditions are described at the scale of the stand, and threshold conditions are defined and applied to real forests.

Table 1. Simulated fuel changes after thinning with moderate slash disposal and subsequent greenup through development of a shrub/herb understory. Values for the thinned and greenup conditions are for demonstration only and not based on real data.

Fuel Parameter*	NFFL Model 9	Thinned Stand	Greenup
1-hr load	2.92	4.00	4.00
10-hr load	0.41	3.00	3.00
100-hr load	0.15	3.00	3.00
Live herb load	0.00	0.00	1.00
Live woody load	0.00	0.00	2.00
Fuel depth	0.20	0.50	0.50

* load in tons/acre, depth in feet

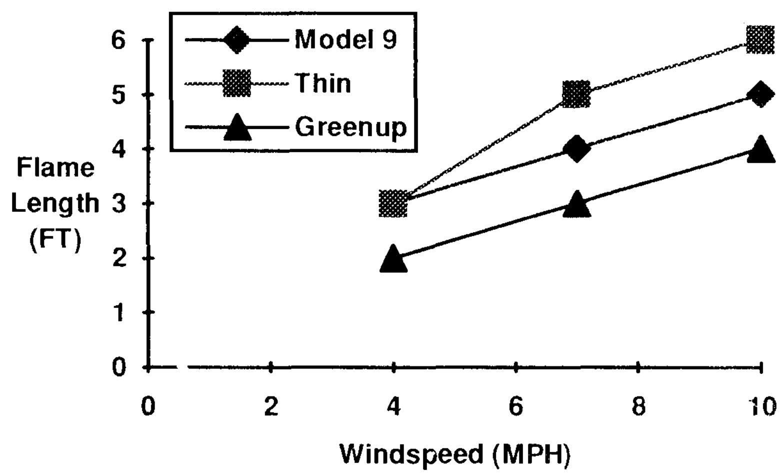

Figure 2. Effect of changing fuel conditions (see Table 1) on potential fire behavior. Environmental conditions are "moderate" with 1-, 10-, and 100-hr fuel moistures at 6, 7, and 8% and live fuel moisture at 120%.

Conditions That Initiate Crown Fire

A fire moving through a stand of trees may move as a surface fire, an independent crown fire, or as a spectrum of intermediate types of fire. The initiation of crown fire behavior is a function of surface fireline intensity and critical parameters of the tree crown layer: its height above ground and moisture content (Van Wagner 1977). The critical surface intensity needed to initiate crowning is:

$$I_0 = (Czh)^{3/2} \qquad \text{(Equation 1)}$$

where

I_0 = critical surface intensity
C = empirical constant, derived as 0.010 (Van Wagner 1977)
z = crown base height
h = heat of ignition (largely a function of crown moisture content)

Therefore, values for critical surface intensity, I_0, can be calculated for a range of crown base heights and foliar moisture contents (Table 2). These represent minimum levels of fireline intensity necessary to initiate crown fire. Equivalent flame lengths in SI and English units are presented in Table 3. For the Table 3 equivalents, Byram's (1959) relation between flame length and fireline intensity was used rather than Thomas' (1963) flame length model. Rothermel (1991) uses Thomas' model, which is based on a 2/3 power law, rather than Byram's square root model, in his technical report on predicting behavior and size of crown fires. However, to describe initiating conditions, Byram's model may be more appropriate, and is used extensively for estimating the flame length of spreading surface fires (Albini 1976, Rothermel 1983). Levels of fireline intensity or flame length below these critical levels may result in fires that do not crown but are still of stand replacement severity. For the limited range of crown base heights and foliar moistures shown in Tables 2 and 3, the critical levels of fireline intensity and flame length appear more sensitive to height to crown base than to foliar moisture.

If the structural dimensions of a stand and information about late summer foliar moisture are known, then critical levels of fireline intensity that will be associated with crown fire for that stand can be calculated. Fireline intensity can be predicted for a range of stand fuel conditions, topographic conditions, and anticipated weather conditions, so it is possible to link on-the-ground conditions with the initiating potential for crown fires. The potential for management to avoid crown fire initiation involves keeping $I < I_0$. This can be accomplished by managing surface fuels such that I is kept well below I_0 (see previous section), or by managing for sufficient crown base heights such that I_0 is large (see Table 2).

Table 2. Critical levels of fireline intensity (kW m^{-1}) associated with initiation of crown fire activity in coniferous stands.

Foliar Moisture Content (%)	Height of Crown Base (m) 2	4	6	8	12	16	20
70	308	871	1600	2463	4526	6968	9737
80	362	1024	1881	2897	5321	8193	11449
90	419	1185	2178	3353	6159	9482	13252
100	479	1354	2488	3830	7036	10833	15140
120	606	1714	3148	4847	8904	13709	19159

Table 3. Flame lengths associated with critical levels of fireline intensity from Table 2, using Byram's (1959) equation.

Foliar Moisture Content (%)	Height of Crown Base meters (nearest foot) 2 (6)	4 (13)	6 (20)	8 (26)	12 (40)	16 (53)	20 (66)
70	1.1 (4)	1.8 (6)	2.3 (8)	2.8 (9)	3.7 (12)	4.6 (15)	5.3 (17)
80	1.2 (4)	1.9 (6)	2.5 (8)	3.0 (10)	4.0 (13)	4.9 (16)	5.7 (19)
90	1.3 (4)	2.0 (7)	2.7 (9)	3.3 (10)	4.3 (14)	5.3 (17)	6.1 (20)
100	1.3 (4)	2.1 (7)	2.8 (9)	3.4 (11)	4.6 (15)	5.6 (18)	6.5 (21)
120	1.5 (5)	2.4 (8)	3.2 (10)	3.9 (13)	5.1 (17)	6.2 (21)	7.3 (24)

Conditions That Allow Crown Fire To Spread

The crown of a forest is similar to any other porous fuel medium in its ability to carry fire and the conditions under which fire will or will not spread. The net horizontal heat flux, E, into the unburned fuel ahead of the fire is described by Van Wagner (1977):

$$E = Rdh \qquad \text{(Equation 2)}$$

where

- E = net horizontal heat flux, kW m^{-2}
- R = rate of spread, m sec^{-1}
- d = bulk density of crown, kg m^{-3}
- h = heat of ignition, kJ kg^{-1}

Crown fuels are typically considered those which interact in the crown fire process, usually needles but possibly including lichens, fine branches, etc. Crown fires will stop if either R or d, the rate of spread or bulk density of the crown, fall below some minimum value.

If surface fireline intensity (I) rises above the critical surface intensity needed to initiate crown fire behavior (I_O), the crown will likely become involved in combustion. However, Van Wagner (1977, 1993) recognizes three types of crown fire behavior that can be described by critical levels of fireline intensity (I) and rates of spread (R): (1) a passive crown fire, in which $I > I_O$, but R is not sufficient to maintain crown fire activity; (2) an active crown fire, where $I > I_O$ and R is above some minimum spread rate; and (3) an independent crown fire, where $I > I_O$ and R through the crown is largely independent of heat from the surface fire intensity I. A "crown-fire-safe" landscape would have characteristics such that, at most, a passive type of crown fire would result under severe fire weather.

Critical conditions can be defined below which active and independent crown fire spread is unlikely. To derive these conditions, visualize a crown fire as a mass of fuel passing by a stationary flaming front (Figure 3). The mass flow rate (S) is the product of rate of spread (R) and crown bulk density (d), and the units of S are Kg m^{-2} sec^{-1}, or mass per unit cross section area of crown per unit time. It can be described in the context of Equation 2:

$$S = Rd = E/h \qquad \text{(Equation 3)}$$

The mass flow rate has some minimum product, S_O, below which crown fire spread will not occur, and that is determined by combinations of the rate of spread (R) and crown bulk density (d). Van Wagner (1977) empirically derived a minimum mass flow rate of $S_O = 0.05$, which he favorably compared to other values in the literature. Therefore, even if conditions are favorable for crown fire initiation, the potential for spread of a crown fire

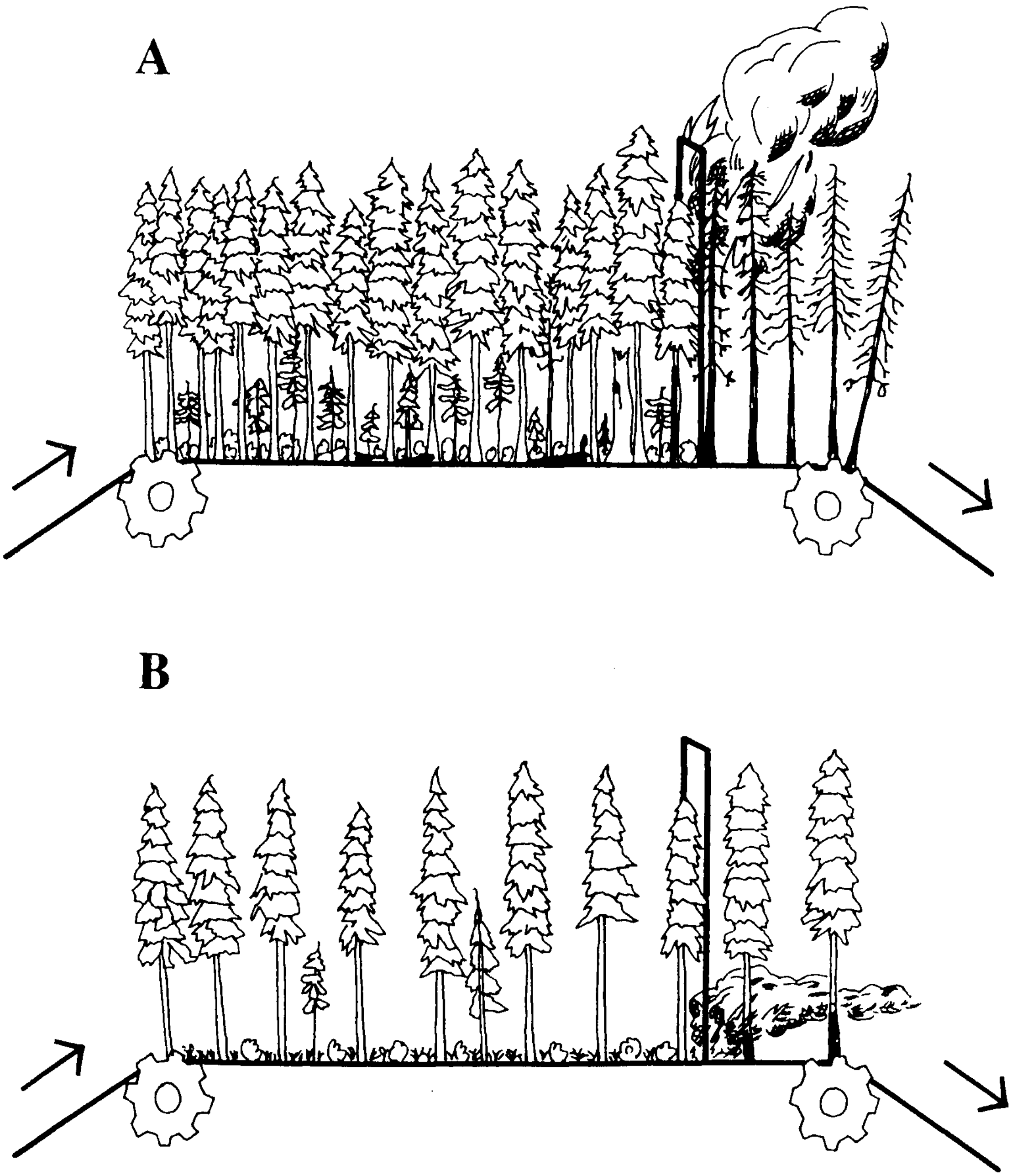

Figure 3. Critical conditions for mass flow rate can be visualized by passing a forest along a "conveyor belt" through a stationary flaming front. A. Under severe fire weather and high rate of spread, crown mass passes through the flaming front rapidly and achieves $S_O > 0.05$, and crown fire occurs. B. Where crown bulk density is lower under the same rate of spread, critical levels of S_O cannot be obtained and the fire remains a surface fire.

can be limited by $S_0 < 0.05$. The problem is thus reduced to one where critical conditions for R (rate of spread) and d (crown bulk density) may be defined, below which crown fires will not spread. Individual crown torching, and crown scorch of varying degrees, may still occur.

Defining a set of critical conditions of R and d that may be defined by management activities is difficult. For given levels of d above some minimum, R could potentially increase in the presence of strong winds and allow an independent crown fire (sensu Van Wagner 1977) to move through a stand. For this exercise, to define conditions such that crown fire spread would be unlikely (that is, products of R and d such that $S_0 < 0.05$), arbitrary thresholds of R were established so that critical levels of d could be defined . The upper threshold for R for this exercise (R_1) was defined as the maximum R of the fires studied by Rothermel (1991), the evening R of the Sundance fire (1967), 1.35 m sec^{-1}. The middle range (R_2) was defined by the maximum R of significant wind-driven fires studied by Rothermel, excluding the evening run of the Sundance fire (Pattee Canyon 1977, Sundance afternoon 1967, Sandpoint 1985, Lily Lake 1980, Mink Creek 1988, Red Bench 1988, Black Tiger 1989), or 0.67 m sec^{-1}. The low end of the range (R_3) was defined by the average maximum R of the runs of these same 7 fires, or 0.40 m sec^{-1}. These provide a reasonable range of threshold values for rate of spread. In boreal forests, Johnson (1992) estimated R of 0.3 m sec^{-1}, with crown bulk densities generally above 0.2 kg m^{-3}. At the 1994 Tyee Fire in Washington, R was estimated at 0.389 m sec^{-1} in mixed conifer forest at Mud Creek (R. Sampson, Tyee fire report), 0.503 m sec^{-1} in mixed conifer forest at Oklahoma Gulch (L. Williams, Tyee fire report), and 1.34 m sec^{-1} in lodgepole pine/subalpine fir forest (B. Walker, Tyee fire report, from table of ROS given temperature/relative humidity and Haines Index), all within the range defined by Rothermel. Given this range of R, and $S_0 = 0.05$, alternative levels of d in equation 3 are calculated as 0.037 (for R_1), 0.074 (for R_2), and 0.125 (for R_3), below which crown fire spread would be very unlikely.

A questionable assumption in this analysis is that R will remain constant as d is drawn down to the critical level. In fact, if R does decline as d is reduced, then in theory a higher level of d might be sustained in the forest without additional risk of crown fire spread. This assumption will be further discussed later.

STAND STRUCTURES AND CROWN FIRE

The preceding analysis has established critical levels of fireline intensity (I) and several possible levels of crown bulk density (d) below which crown fire initiation and spread are unlikely. From these levels, and with additional information on fire weather, surface fuel characters, and stand characters, "crown-fire-safe" conditions for forest stands may be defined. It should be emphasized that a "crown-fire-safe" forest is neither fireproof nor likely to escape free of wildfire damage at the stand level. It is a stand which is unlikely to generate or allow the spread of crown fire. Wildfire damage will clearly be less than in unmanaged stands, but will not necessarily be low or absent. Management of surface fuels is a corollary activity that can constrain surface fire intensity and reduce chances of crown fire activity and damage to the residual stand.

Crown bulk densities (d) were calculated for ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), and grand fir (*Abies grandis*) for several diameter/density combinations. Crown fuel biomass and crown volume were used to construct a mass/volume ratio (e.g., crown bulk density) for each species, size class, and density. Crown fuel as defined for this report includes all foliar biomass plus 50 percent of other 1-hour timelag fuels (0 - 0.62 cm) in the crown. Other fine fuels such as lichens were ignored for this exercise, but would be critical for some species in other forest types (such as subalpine fir [*Abies lasiocarpa*]). The "other" fuels here are twigs and fine branches. Half of the fine branch category was considered small enough to contribute significant energy during the crown combustion process, interpreted from data in Anderson (1969). Foliar biomass of dominants by tree species and size class was calculated from data of Brown (1978) and Gholz et al. (1979), using averages where data were available for a species in both sources. Fine branch fuel additions were added using Brown's (1978) ratio of foliar biomass to 1-hr timelag size class for each of the three species. The proportion (at the 50% level) of 1-hr timelag fuels to foliar biomass ranged from 11-1% for small to large ponderosa pine, 26-20% for small to large Douglas-fir, and 21-17% for small to large grand fir. Crown lichen biomass was not considered in this analysis, but would increase crown flammability for those species containing significant amounts: grand fir and subalpine fir.

At high tree densities, aggregating the crown fuel by simple multiplication of tree biomass times density can result in overestimating biomass. The total biomass per sites was capped at 50 tonnes ha^{-1} (about 20 t ac^{-1}). This is a high crown fuel load (see Rothermel 1991) and probably results in some overestimation of crown bulk density, but only at very high tree densities of large trees. These combinations are well beyond the possible critical levels of d defined earlier, so are relatively unimportant in evaluating <u>critical</u> bulk densities.

Crown volumes were determined from Brown (1978) for each of the three species by size class. Live crown length was used as the criterion for crown volume, so that dead branches below the live crown were not considered for any of the three species. Generally, the bulk density of dead branches below the tree crown will be too low to generate crown fire activity, although lower branches may help to sustain flame activity up into the crown from surface fuel combustion.

Crown bulk densities for the three species by size class and density showed some consistent trends (Table 4). Crown bulk densities were generally lowest for ponderosa pine, intermediate for Douglas-fir, and highest for grand fir. For any given density of trees, crown bulk density increased with tree size, suggesting crown fuel biomass increased more than crown volume as tree size increased. For any given tree size, crown bulk density increased with tree density.

Table 4. Crown bulk density (kg m3) by diameter class and density for ponderosa pine (regular type, first row of each triplet), Douglas-fir (bold type, middle row), and grand fir (italics, third row).

Average Diameter	Tree Density Per Hectare						
(dbh - cm)	50	100	200	400	800	1600	3200
Inches	20	40	81	162	324	648	1295 TPA
1.27	.001	.002	.005	.009	.018	.036	.073
0.5	**.002**	**.003**	**.005**	**.011**	**.022**	**.043**	**.088**
	.002	*.003*	*.007*	*.014*	*.027*	*.055*	*.110*
7.62	.003	.007	.014	.028	.055	.111	.223
3.0	**.004**	**.007**	**.014**	**.028**	**.056**	**.113**	**.226**
	.006	*.012*	*.024*	*.047*	*.094*	*.189*	*.378*
19.05	.005	.010	.021	.041	.083	.166	.333
7.5	**.009**	**.017**	**.034**	**.068**	**.136**	**.272**	**.545**
	.008	*.016*	*.033*	*.066*	*.132*	*.263*	*.409*
31.75	.010	.020	.041	.082	.164	.328	.397
12.5	**.012**	**.025**	**.049**	**.099**	**.198**	**.353**	**.353**
	.013	*.026*	*.052*	*.103*	*.206*	*.287*	*.287*
44.45	.011	.023	.047	.095	.190	.292	------
17.5	**.019**	**.039**	**.078**	**.155**	**.310**	**.313**	-------
	.023	*.047*	*.095*	*.190*	*.247*	*.247*	-------
63.5	.031	.062	.124	.248	.361	------	------
25.0	**.023**	**.048**	**.096**	**.191**	**.252**	------	-------
	.023	*.047*	*.095*	*.247*	*.247*	------	-------
101.6+	.033	.066	.133	.194	------	------	------
40+	**.042**	**.083**	**.167**	**.210**	------	------	-------
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Missing data in cells denotes either crown bulk densities with unrealistic size/density combinations or cells for which data were not available.

The critical bulk density for independent crown fire spread can be evaluated in terms of Table 4. For example, if the middle value of maximum crown fire rate of spread (R) were chosen as a planning criterion, then the critical d would be 0.074 kg m^3. It would be reached first by grand fir, and last by ponderosa pine, for a comparable set of tree sizes and densities. The differences between species are not as great as the differences between densities and size classes for these three species, suggesting control of stand structure is more important than species. However, in terms of fire tolerance in the presence of a surface fire, choice of species will be critical, as some species will develop fire tolerance much faster than others, and some may never adapt because of thin bark. The data in Table 4 are for pure stands of one species. Crown bulk densities of combinations of species, such as a 50-50 mix of Douglas-fir and ponderosa pine, show little difference from the pure species tables, but make an important assumption: that there will not be crown stratification. Stratification will be very important where one species can maintain itself in subordinate crown positions, which will affect both biomass and crown volume, and therefore crown bulk density. Stratification can also affect height to crown base. Again, it must be stressed that these tables are specific to single-sized, non-stratified stands.

AN EMPIRICAL TEST OF THE CROWN BULK DENSITY THRESHOLD

Limited empirical information exists to evaluate the predictability of the crown bulk density threshold. Much of the existing data is from boreal forest types (Van Wagner 1977, 1993). Crown fire activity in several stands burned in the 1994 Wenatchee fires were evaluated where changes in crown fire activity occurred. Data on stand diameter and density were gathered by Forest Service personnel in several stands Some of the stands had also been treated with prescribed burning or pile burning to limit critical levels of fireline intensity (I_O) from occurring, but all may serve as empirical tests of crown bulk density thresholds. Crown bulk densities were calculated from the stand characteristics information, and related to presence or absence of crown fire activity (Table 5). Unthinned stands tended to be crown stratified, and the use of these tables may have biased the estimates somewhat for those stands.

The 1994 fires appeared to have a bulk density threshold of $d \cong 0.10$ kg m^3, with crown fire activity likely above the threshold and no crown fire activity below it. Typically in this area, unthinned stands have $d > 0.10$ while thinned stands do not. In each case where a thinned-unthinned comparison was possible, crown fires in adjacent unthinned stands dropped to the ground as surface fires when they reached the thinned stands. In every case, the unthinned and thinned stands were less than 100 year old stands with mixes of Douglas-fir and ponderosa pine. The critical level of d empirically derived here fits halfway between the levels of d derived from R_1 ($d = 0.074$) and R_2 ($d = 0.125$). The apparent increase in critical levels of d above R_1 may suggest that maximum rates of R decline as crown bulk density decreases. In the 1994 fires, it appears that $d = 0.10$ is about the highest crown bulk density a stand can maintain and avoid the potential for crown fire behavior.

Table 5. Relation of estimated crown bulk density to crown fire behavior. Stands are ranked in descending order of crown bulk density.

Location	Stand and Treatment	Average Stand Diameter (cm [in])	Average Stand Density (t ha^{-1} [ac])	Estimated Crown Bulk Density, d (kg m^{-3})	Comments on Fire Behavior
Vicinity Mallen Ranch	MC-unthinned	17 [7]	1700 [689]	≅ 0.15	Crown fire activity
Vicinity Marsh Residence	MC-unthinned	17 [7]	1700 [689]	≅ 0.15	Crown fire activity
Navarre Coulee	MC-unthinned	17 [7]	1000 [400]	≅ 0.10	Crown fire activity
Vicinity Mallen Ranch	MC-thinned	30 [12]	500 [200]	≅ 0.09	Crown fire stops
Navarre Coulee	MC-thinned	30 [12]	250 [100]	≅ 0.05	Crown fire stops
Mud Creek	MC-thinned	30 [12]	250 [100]	≅ 0.05	Crown fire stops
Marsh Residence	MC-thinned	24 [9.5]	225 [91]	≅ 0.035	Crown fire stops

At levels of d near the threshold, fuel treatment may help to reduce the chances of crown fire activity. Two of the case examples (Table 5) were near the threshold. Navarre Coulee, a stand with no fuel treatment, was at the crown bulk density threshold and exhibited crown fire behavior. At the Vicinity Mallen Ranch site, pruning and pile burning of thinning/pruning debris reduced the fuel ladder effect and limited $I < I_0$, so that a running crown fire dropped to the ground there even though d was relatively high.

Crown bulk density can be used as a criterion to limit crown fire behavior. By maintaining stands at crown bulk densities (d) of <0.10 kg m^3, active or independent crown fire activity can be limited. Such a criterion has both advantages and limitations. The advantages include (1) that empirical evidence seems to support the existence of such a threshold; (2) that d can be calculated from typical stand exam data, so that crown fire risk can be evaluated at the stand level; and (3) that silvicultural prescriptions can be designed at the stand level to include protection from crown fire, to make "crown-fire-safe" forests. Limitations of using this criterion are (1) that fire may still burn through stands and do significant damage depending on the size and species of trees; (2) although stands can be made "crown-fire-safe", we do not currently know how much of the landscape need be treated this way to make a "crown-fire-safe" landscape; (3) that other competing and important objectives may limit the scale of such treatments on the landscape; and (4) higher elevation forests have naturally burned this way for millennia, so that attempts to limit crown fire activity may be ecologically and economically cost-effective only in the lower elevation forests.

Several constraints to this analysis exist. The effect of slope was not considered, stands with non-stratified crowns were assumed, and crown bulk densities were calculated from crude data. More validation of dimensions of stands where crown fires have been observed to drop to the ground is needed.

DISCUSSION

It is clear that forest structure can be manipulated to reduce the severity of fire events. The challenge is to meld fuel strategies with other forest management objectives, and being able to select proper fuel treatments and priorities for treatment. In general, forests with low severity fire regimes should have highest priority for treatment, and that priority should decline in the high severity fire regimes. The low severity fire regimes (such as mixed conifer) have undergone the most change since fire exclusion policies were enacted, and have high levels of both risk (chance of a fire starting) and hazard (fuels and their condition, such as low fuel moisture). In the low severity fire regimes, strategies that address both surface and crown fire potential are more likely to be adopted than in the moderate to high severity fire regimes, where if fuel treatments are applied they will have a less significant effect due to generally lower risk.

In a conceptual sense, treatments can be considered either "moderate" or "intensive". Moderate treatment areas are those where the fuel management objective may focus on reduction of potential surface fire intensity, so that $I < I_0$. Fires moving through these forests will have less chance of crowning potential. Low thinning, pruning, and surface fuel treatment with pile or broadcast burning might be among the fuel reduction techniques applied. Intensive management includes the techniques above plus management of crown bulk density < 0.10 kg m^3, so that even under severe fire weather the fire is likely to remain a surface fire. In both treatments, fire is still likely to occur, but the chances of effective fire suppression will be higher. Fire severity in areas burned may be lower, but if the trees are small or are of less fire-resistant species, the wildfire effect may still be severe.

Where fuel management priority is high, there is still much uncertainty about how treatments should be applied. Rather than attempt a "one-size-fits-all" approach, there may be instead a combination of approaches that can be applied to each situation depending upon the forest type and competing objectives (Figure 4). The gradient of treatment on a landscape ranges from no treatment at all to intensive treatment over the entire area. Some intermediate steps (others are possible) are shown in Figure 4 and include "interior" no treatment areas surrounded by intensive treatment areas, or no treatment enclaves surrounded by areas with moderate to intensive treatment.

Landscape Fuel Management Alternatives

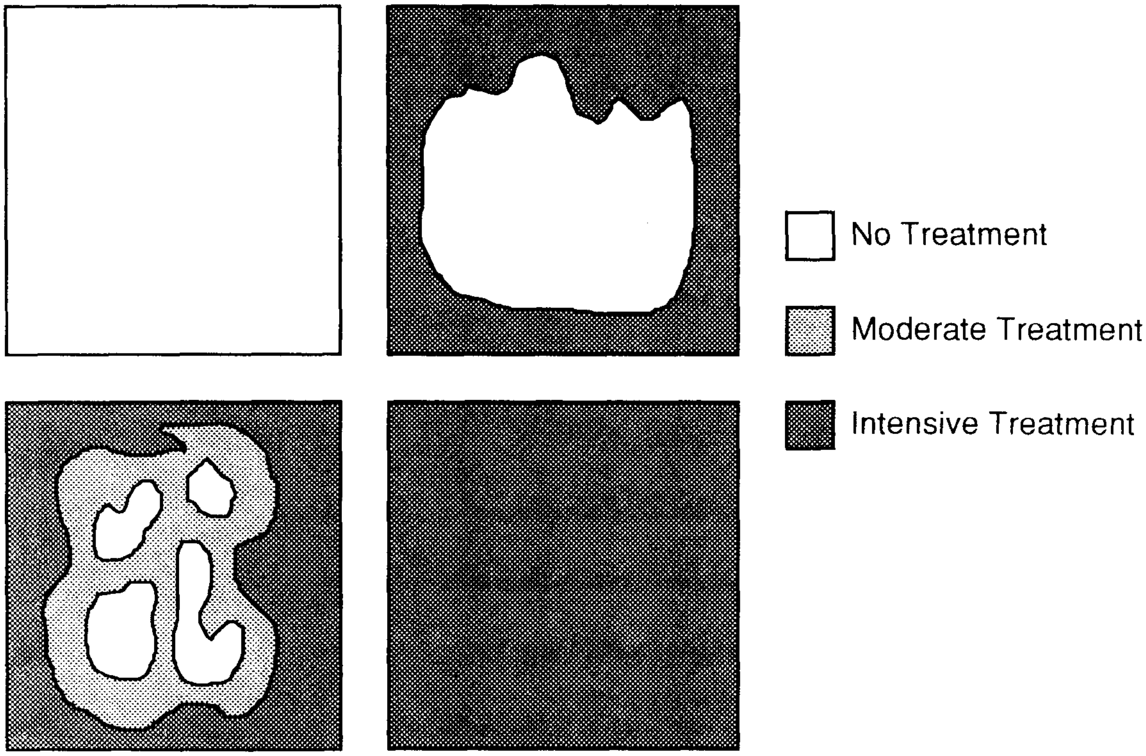

Figure 4. Landscape level approaches to fuel management cross a gradient from no treatment to intensive treatment across the entire landscape. Intermediate approaches (upper right, lower left) combine some area of no treatment with other areas where moderate to intensive treatments are applied. In these example, moderate treatments address reduction of surface fire intensity; intensive treatments address both surface fire and crown fire intensity.

The $64,000 question remains: how much of a landscape need be treated to make it relatively fire-safe? The answer to this question does not depend on fuels management alone. Some of these treatments can pay for themselves; others will not, so will depend on how much money is available, and how it can be distributed. Fuel treatment requires access, so that "no treatment" areas may by default include areas where roads are not in place as well as areas where specific forest structures (such as late-successional forest) are desired. However, even if the answers to these peripheral questions are available, we really don't know how to completely answer the fuel management question, except to say that as more of the landscape is treated, it becomes more "firesafe". In the 1994 Wenatchee fires, areas that had been thinned and prescribed burned over the last 20 years had significantly reduced fire behavior, but the tops of the stands were scorched from heat produced at other places on the landscape that had not been treated. The treated areas were at a scale of several hundred acres, and clearly were not large enough to be effective at reducing fire severity, as most of the scorched trees died.

We have made some great strides in understanding the effects of forest structure on fire behavior, but some major challenges remain. These challenges are largely landscape-level issues, similar to many other of our current forest management challenges.

LITERATURE CITED

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press. Covelo, CA.

Albini, F. 1976. Estimating wildfire behavior and effects. USDA For. Serv. Gen. Tech. Rep. INT-30.

Anderson, H.E. 1969. Heat transfer and fire spread. USDA For. Serv. Res. Pap. INT-

Brown, J.K. 1978. Weight and density of crowns of Rocky Mountain conifers. USDA For. Serv. Res. Pap. INT-197.

Buckley, A.J. 1992. Fire behaviour and fuel reduction burning: Bemm River wildfire, October, 1988. Australian Forestry 55: 135-147.

Burgan, R., and R.C. Rothermel. 1984. BEHAVE: Fire behavior prediction and fuel modeling system - FUEL subsystem. USDA Forest Service Gen. Tech. Rep. INT-167.

Byram, G.M. 1959. Combustion of forest fuels. In: Brown, K.P. (ed) Forest fire: Control and use. McGraw Hill. New York.

Gholz, H.A., C.C. Grier, A.G. Campbell, and A.T. Brown. 1979. Equations for estimating biomass and leaf area of plants in the Pacific Northwest. Forest Research Lab Res. Pap. 41. Oregon State University. Corvallis, Oregon. 39 pp.

Helms, J.A. 1979. Positive effects of prescribed burning on wildfire intensities. Fire Management Notes 40: 10-13.

Johnson, E.A. 1992. Fire and vegetation dynamics: Studies from the North American boreal forest. Cambridge University Press. Cambridge, U.K. 129 pp.

Keane, R., E.D. Reinhardt, and J.K. Brown. 1995. FOFEM: A first order fire effects model. p. 214 In: Proceedings: Symposium on fire in wilderness and park management. USDA For. Serv. Gen. Tech. Rep. INT-GTR-320.

Rothermel, R. 1983. How to predict the spread and intensity of forest and range fires. USDA For. Serv. Gen. Tech. Rep. INT-143.

Rothermel, R. 1991. Predicting behavior and size of crown fires in the northern Rocky Mountains. USDA For. Serv. Gen. Tech. Rep. INT-438.

Thomas, P.H. 1963. The size of flames from natural fires. In: Proceedings, ninth symposium (international) on combustion: 1962 August 27 - September 1; Ithaca, NY. New York: Academic Press.: 844-859.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research 7: 23-34.

Van Wagner, C.E. 1993. Prediction of crown fire behavior in two stands of jack pine. Canadian Journal of Forest Research 23: 442-449.

Weatherspoon, C.P., and C.N. Skinner. 1995. An assessment of factors associated with damage to tree crowns from the 1987 wildfires in northern California. Forest Science 41: 430-451.