3D.5 FUELS PLANNING: MANAGING FOREST STRUCTURE TO REDUCE FIRE HAZARD

David L. Peterson[a], Morris C. Johnson[a], James K. Agee[b],
Theresa B. Jain[c], Donald McKenzie[a], and Elizabeth D. Reinhardt[d]

[a]U.S.D.A. Forest Service, Pacific Northwest Research Station, 400 N. 34th St. Suite 201, Seattle, WA 98103
[b]College of Forest Resources, University of Washington, P.O. Box 352100, Seattle, WA 98195
[c]U.S.D.A. Forest Service, Rocky Mountain Research Station, 1221 South Main St, Moscow, ID 83843
[d]U.S.D.A. Forest Service, Rocky Mountain Research Station, 800 East Beckwith, P.O. Box 8089, Missoula, MT 59807

1. INTRODUCTION

Prior to the 20th century, low intensity fires burned regularly in most arid to semiarid forest ecosystems, with ignitions caused by lightning and humans (e.g., Baisan and Swetnam 1997, Allen et al. 2002, Hessl et al. 2004). Low intensity fires controlled regeneration of fire sensitive (e.g., grand fir [*Abies grandis*]) species (Arno and Allison-Bunnell 2002), promoted fire tolerant species (e.g., ponderosa pine [*Pinus ponderosa*], Douglas-fir) [*Pseudotsuga menziesii*], maintained an open forest structure (Swetnam et al. 1999), reduced forest fuel loads, decreased the impacts of insects, and maintained wildlife habitat for species that require open stand structures (Fulé et al. 1997, Kalabokidis et al. 2002). Fire exclusion has caused the accumulation of understory vegetation and fuels, greater continuity in vertical and horizontal stand structure, and increased potential for crown fires (Dodge 1972, van Wagner 1977, Arno and Brown 1991, Agee 1993).

The concept of Condition Class (*sensu* Schmidt et al. 2002) uses current fuel conditions to represent the degree of departure from historical fuel conditions at a coarse spatial scale. Approximately 59% of Fire Regime 1 forests in the western United States have higher fuel accumulations (currently Condition Classes 2 and 3) than they would have historically, and approximately 43% of Fire Regime 2 forests have higher fuel accumulations (currently Condition Class 3) than they would have historically (Schmidt et al. 2002). In the inland northwestern United States, forests that would currently burn with high severity comprise 50% of the forest landscape compared to only 20% historically (Quigley et al. 1996).

Vertical arrangement and horizontal continuity of many arid and semiarid low-elevation forests in the western United States differ from historical stand structures (Mutch et al. 1993, Carey and Schumann 2003). Current forests have denser canopies, more fire-intolerant species, and fewer large trees (Parsons and DeBenedetti 1979, Bonnicksen and Stone 1982). These conditions increase the probability of surface fires developing into crown fires, because understory ladder fuels lower the effective canopy base height of the stand (Laudenslayer et al. 1989, MacCleery 1995, Scott and Reinhardt 2001), where canopy base height is the average height from the ground of the lowest living fire foliage in a forest stand (see quantitative definitions discussed later). This departure from historical conditions is common in high frequency, low to moderate severity regimes (Arno 1980; Agee 1991, 1993, 1994; Skinner and Chang 1996; Taylor and Skinner 1998).

In this paper, we summarize scientific principles that link silvicultural treatments to fire hazard for dry forests in the western United States, and provide a decision-making process for planning fuel treatments. Our objective is to inform on-the-ground implementation of fuel treatments, facilitate interaction between fire managers and silviculturists, and encourage a consistent approach for linking forest structure and fire hazard. A science-based quantitative framework for fuel treatments will assist the environmental analyses needed for the national mandate to manage fuels more effectively.

2. MODIFYING FIRE HAZARD: FUELS AND FOREST STRUCTURE

Fire hazard for any particular forest stand or landscape reflects the potential magnitude of fire behavior and effects as a function of fuel conditions. Understanding the structure of fuelbeds and their role in the initiation and propagation of fire is the key to developing effective fuel management strategies. Fuels have been traditionally characterized as crown fuels (live and dead material in the canopy of trees), surface fuels (grass, shrubs, litter, and wood in contact with the ground surface), and ground fuels (organic soil horizons, or duff, and buried wood). A more refined classification separates fuelbeds into six strata: (1) tree canopy, (2) shrubs/small trees, (3) low vegetation, (4) woody fuels, (5) moss, lichens, and litter, (6) ground fuels (duff) (Sandberg et al. 2001). Each of these strata can be further divided into separate categories. Modification of any fuel stratum has implications for fire behavior, fire suppression, and fire effects (Figure 1).

2.1 Crown Fire

Crown fires are generally considered the primary threat to ecological and human values, and are the primary challenge for fire management. The *tree canopy* is the primary stratum involved in independent crown fires, and the spatial continuity and density of tree canopies combine with fuel moisture and wind to determine rate of fire spread and severity (Rothermel 1983). The *shrub/small tree* stratum is also involved in crown fires by increasing surface fireline intensity and serving as "ladder fuels" that provide continuity from the surface fuels to canopy fuels, thereby potentially facilitating active crown fires.

Corresponding author address: Dave Peterson, U.S.D.A. Forest Service, Pacific Northwest Research Station, 400 N. 34th St. Suite 201, Seattle, WA 98103

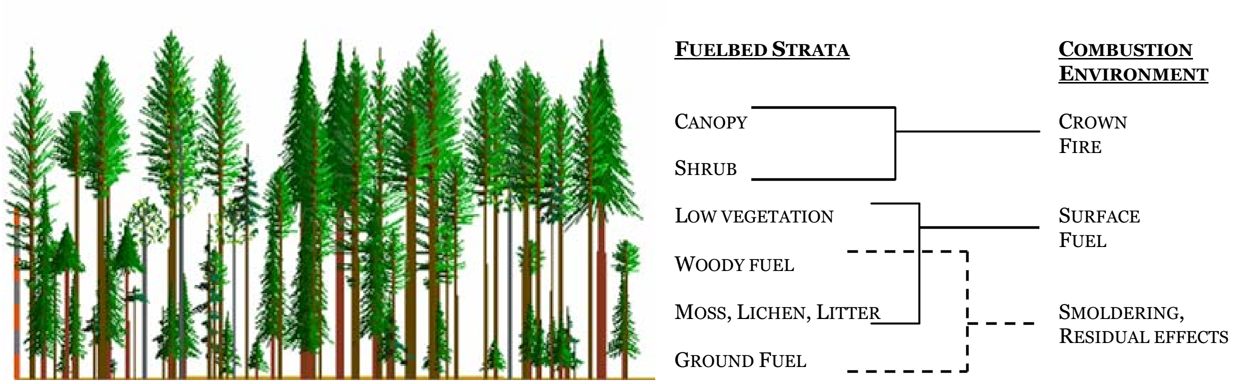

Figure 1. Fuelbed strata affect the combustion environment, fire propagation and spread, and fire effects.

Passive crown fires (torching) kill individual trees or small groups of trees. *Active crown fires* (continuous crown fire) burn the entire canopy fuel complex but depend on heat from surface fuel combustion for continued spread. *Independent crown fires* burn canopy fuels independently of heat from surface fire, because the net horizontal heat flux and mass flow rate (a product of rate of spread() and canopy bulk density in the crown are sufficient to perpetuate fire spread.

Crown fires occur when surface fires create enough energy to preheat and combust fuels well above the surface (Agee 2002). Crown fire begins with torching, or movement of fire into the crown, followed by active crown fire spread in which fire moves from tree crown to tree crown through the canopy (van Wagner 1977, Agee et al. 2000). Torching occurs when the surface flame length exceeds a critical threshold defined by moisture content of fuels in the canopy and canopy base height (van Wagner 1977, Scott and Reinhardt 2001). Foliage moisture varies within a tree, with newer foliage generally having higher moisture than older foliage, and varies during the course of a year, depending on the local climatic regime.

The canopy base height, defined as the lowest height at which there is at least 0.011 kg m^{-3} of canopy fuel (Scott and Reinhardt 2001), determines how critical the moisture factor can become. For example, if foliage moisture averages 100% in late summer, a height to live crown of 2 m means any surface fire with a flame length exceeding 1.3 m would likely produce torching. If the bottom of the crown is lifted to 6 m, the predicted critical flame would be 2.7 m, so a much more intense surface fire would be needed to initiate a crown fire.

Active crown fire spread typically begins with torching, and is a function of canopy bulk density and rate of spread (van Wagner 1977). Canopy bulk density must be high enough to carry the fire through the tree canopy, and canopy bulk density therefore varies depending on rate of spread. This rate is defined as a function of crown fire rate of spread and canopy bulk density. Where empirical rates of spread from observed fires (Rothermel 1991) are used, crown fire Hazard can effectively be represented by canopy bulk density. Below a critical threshold of canopy bulk density (a function of fire weather and fire rate of spread) a crown fire can make a transition back to a surface fire (Agee 2002).

2.2 Principles of Fuel Treatment

Fuel treatments should take into account the effects of *canopy base height, canopy bulk density, and continuity of tree canopies* on the initiation and propagation of crown fire. Although canopy base height plays a key role in initiating crown fire, it is difficult to quantify in the field even for experienced fire managers, because its location in a given forest stand is highly subjective. Canopy bulk density is the foliage (mass of available fuel) contained per unit crown volume (kg m^{-3}) of a forest stand. This parameter has been accurately quantified in only a few forest stands in the United States and is difficult to assess because intensive data collection is required to measure it. Continuity of canopies varies spatially as a function of the adjacency of tree crowns, but clearly horizontal patchiness of the canopy will reduce the spread of fire within the canopy stratum.

Fuel treatment must consider (1) how a forest stand is accessed and mechanically treated, (2) what material is removed, and (3) what material remains on site in terms of species, sizes, and fuel composition (e.g., sound vs. rotten wood) (Kalabokidis and Omi 1998). Management of thinning residues affects the post-thinning combustion environment, with an almost certain increase in coarse and fine fuels if stems and foliage are left on site (Carey and Schumann 2003). Ground-based equipment (e.g., a feller buncher) typically changes the spatial distribution of fuels. Equipment that removes large stems from the stand prior to further processing will increase the fuel load less than felling and processing within the stand. Helicopter yarding and cable-based systems increase surface fuels unless slash from tree crowns is removed.

Thinning mainly affects standing vegetation; other types of fuel treatments are needed to modify the combustion environment of surface fuels (Fitzgerald 2002). Fire intensity in thinned stands is significantly reduced only if thinning is accompanied by reducing and altering the arrangement of surface fuels created from the thinning operation (Graham et al. 1999). Prescribed burning is also frequently used to reduce surface fuels. The effectiveness of prescribed fire depends on weather, initial fuel conditions and skill of the fire manager. It can be safely conducted only if the probability of crown fire initiation is low. This means that burning must be done where ladder fuels are absent or during moist periods when they are unlikely to combust.

2.3 Thinning as a Fuel Treatment

Silvicultural thinning is implemented with the objective of reducing fuel loads and ultimately modifying fire behavior, but in some cases thinning activities can increase fine fuel loads and understory regeneration, thereby making fire behavior more severe (Agee 1996, Weatherspoon 1996). In addition, removal of larger, more fire resistant trees through thinning may result in high rates of damage to the residual smaller (and less fire resistant) trees in a subsequent fire (Weatherspoon and Skinner 1995). Thinning can in some cases alter stand structure and microclimate such that local fire weather conditions become worse. For example, removal of trees from the canopy and understory can increase surface wind movement (Albini and Baughman 1979), thereby facilitating surface fires and crown fires (Scott and Reinhardt 2001). Stand openings increase solar radiation in the crown and on the ground, and enhance wind circulation, which facilitates drying of live and dead fuels (Pollet and Omi 2002). This can effectively extend the duration of the fire season, because fuels will be dry enough to burn earlier in the year. The potential beneficial versus detrimental effects of thinning and prescribed burning must be carefully assessed for each stand and landscape.

Thinning and prescribed fire target different components of the fuelbed of a given forest stand or landscape. Thinning is potentially effective at reducing the probability of crown fire spread, and is precise in that specific trees are targeted and removed from the fuelbed. Thinning is expensive and poses a challenge for handling large amounts of woody material, much of which may be unmerchantable. Prescribed burning is a less precise management tool, although it can be highly effective at reducing surface fuels and in some cases ground fuels. It is typically cheaper per unit area than thinning and can in some cases be used to reduce stem density and ladder fuels by killing (mostly) smaller trees.

The type and sequence of fuel treatments depend on the amount of surface fuel present; the density of understory and mid-canopy trees (Fitzgerald 2002); long-term potential effects of fuel treatments on vegetation, soils, and wildlife; and short-term potential effects on smoke production (Huff et al. 1995). In forests that have not experienced fire for many decades, multiple fuel treatments are often required. Thinning followed by prescribed burning reduces canopy, ladder, and surface fuels, thereby providing maximum protection from severe fires in the future. Given current accumulations of fuels in some stands, multiple prescribed fires – as the sole treatment or in combination with thinning – may be needed initially, followed by long-term maintenance burning or other fuel reduction (e.g., mowing), to reduce crown fire hazard.

Observations from the Hayman Fire in Colorado and Cone Fire in California in 2002 suggest that past thinning treatments (Skinner 2003) and prescribed fire treatments (Graham 2002) effectively reduced fire behavior on relatively gentle slopes, with crown fires diminishing to surface fires in stands with lower stem densities and surface fuels. Stand structure and wildfire behavior are clearly linked (Biswell 1960, Cooper 1960, Dodge 1972, van Wagner 1977, Rothermel 1991, McLean 1993), so fuel reduction treatments are a logical solution to reducing extreme fire behavior. Extreme fire weather can override even intensive fuel treatments that remove large amounts of fuel. This is especially true under high winds and on steep slopes, conditions that facilitate rapid spread of crown fire and long-distance transport of burning embers (spotting).

3. TOWARD QUANTITATIVE FUEL TREATMENT GUIDELINES

Management of fuels across landscapes, not just individual stands, is required to effectively reduce both the area and severity of fires, and their effects on local communities. In addition, because a small proportion of fires (approximately 1%) is responsible for as much as 98% of the fire area (Strauss et al. 1989), managers need fuel treatment options that are effective under extreme fire weather and in steep mountain topography – conditions under which crown fire spreads most rapidly and burns most severely.

3.1 Silvicultural Thinning

Silvicultural options for fuel treatment are summarized in Graham et al. (1999) and Fitzgerald (2002), who provide visual displays of thinning treatments and explain how treatments address fuel loading. Thinning, the removal of specific components of the tree stratum to meet the management objective of modifying fire hazard, uses several different methods: (1) crown thinning, (2) low thinning, (3) selection thinning, (4) free thinning, (5) geometric thinning, and (6) variable density thinning. The effects of thinning on different forest canopy components are compared in Table 1, and three thinning treatments are displayed in comparison with an unthinned stand (Figure 2). Regeneration treatments, such as shelterwood and seed tree, can also raise canopy base height, decrease canopy bulk density, and decrease surface fuels, depending on how they are applied.

Crown thinning (thinning from above) removes trees with larger diameters but favors the development of the most vigorous trees of these same size classes (Figure 3). Most of the trees that are cut come from the codominant class, but any intermediate or dominant trees interfering with the development of residual trees (sometimes termed crop trees if timber production is an objective) are also removed. Thinning from above focuses on removal of competitors to release suppressed trees.

Low thinning (thinning from below) primarily removes trees with smaller diameters. This method mimics mortality caused by intraspecific and interspecific competition or abiotic factors such as wildfires (Figure 4). Thinning from below primarily targets intermediate and suppressed trees, although codominant and dominant tree are not exempt from harvest, depending on the target reduction in basal area. If codominant and dominant trees are removed, all smaller, intermediate and overtopped trees are also removed (Smith et al. 1997).

Table 1. Effects of thinning treatments on key components of canopy structure related to crown fire.

Thinning treatment	Canopy base height	Canopy bulk density	Canopy continuity	Overall effectiveness
Crown	Minimal	Reduced in upper canopy, but minimal effect in lower canopy	Reduced in upper canopy, but minimal effect in lower canopy	May reduce crown fire spread slightly; but torching unaffected
Low	Large increase if unmerchantable small trees are also removed	Large decrease in lower canopy, some effect in upper canopy depending on tree sizes removed	Large decrease in lower canopy, some effect in upper canopy depending on tree sizes removed	Will greatly reduce crown fire initiation and torching
Selection	None	Reduced continuity in upper canopy, but minimal effect in lower canopy	Reduced continuity in upper canopy, but minimal effect in lower canopy	May reduce crown fire spread slightly if many trees removed; torching unaffected
Free	Small to moderate increase, depending on trees removed	Small to moderate decrease throughout canopy, depending on trees removed	Small to moderate decrease throughout canopy, depending on trees removed	May reduce crown fire spread slightly if many trees removed; torching reduced slightly
Geometric	None	Small to moderate decrease throughout canopy, depending on spacing and species composition	Small to moderate decrease throughout canopy, depending on spacing and species composition	Crown fire spread and initiation reduced if spacing is sufficiently wide; torching reduced
Variable density	Increase in patches where trees are removed	Decrease in patches where trees are removed	Moderate to large decrease	Crown fire spread reduced, crown fire initiation reduced somewhat; torching reduced somewhat

Selection thinning removes dominant trees with the potential objective of stimulating the growth of smaller trees. This practice, commonly called "high grading," removes the most economically valuable trees, and has limited applicability in forest management programs with multiple objectives (e.g., structural diversity, wildlife habitat) because it limits future stand options.

Free thinning primarily favors selected individual trees in a stand while the rest of the stand remains untreated (Figure 5). Cuttings are designed to release residual trees regardless of their position in the crown canopy. The method is commonly used to increase structural diversity in forest stands.

Geometric thinning removes trees based on predetermined spacing (e.g., 2x2 m spacing) or another geometric pattern, with little regard for their position in the crown canopy. Geometric thinning is often applied in young plantations with high density. Ordinarily, mechanical thinning is employed only in the first thinning of a stand. Space and row thinning are two general patterns followed in mechanical thinning.

Variable density thinning combines low thinning and one or more of the other techniques by removing trees from some patches and leaving small stands of trees in other patches. This technique reduces fuel continuity within the canopy, thereby reducing crown fire hazard. For any target stem density, variable density thinning generally increases spatial heterogeneity of trees and canopy structure. This technique can promote better habitat characteristics for certain types of plants and animals.

Graham et al. (1999) provide examples of how specific thinning treatments affecting stand density, canopy base height, and canopy bulk density can be linked with fire behavior fuel models (Anderson 1982) to determine if surface fire will propagate to crown fire following fuel treatments. Scott and Reinhardt (2001) provide the conceptual and quantitative framework for a more detailed analysis of the potential for transitions from surface fire to crown fire. The Fire and Fuels Extension to the Forest Vegetation Simulator (Reinhardt and Crookston, in press) incorporates much of this analytical capability. It allows users to enter current stand and surface fuel conditions; simulate thinning treatments, mechanical fuel treatments, and fire; and to examine the effects of these treatments on surface fuels, canopy fuels, and potential fire behavior over time. Indices of crown fire hazard ("torching index" and "crowning index," Scott and Reinhardt 2001) are provided to help assess the effectiveness of fuel treatments on crown fire potential.

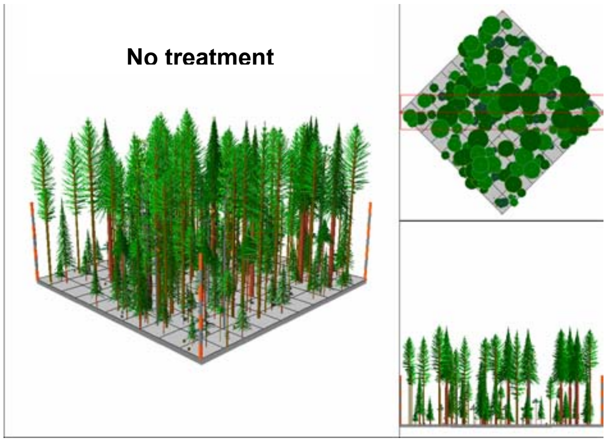

Figure 2. A 70-year old, unthinned mixed conifer stand.

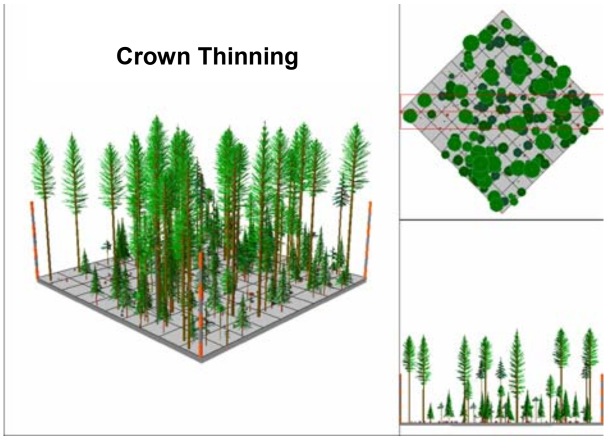

Figure 3. A 70-year old mixed conifer stand, showing the results of crown thinning.

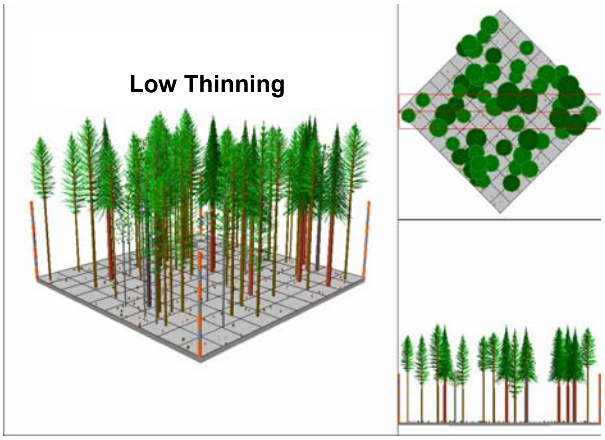

Figure 4. A 70-year old mixed conifer stand, showing the results of low thinning.

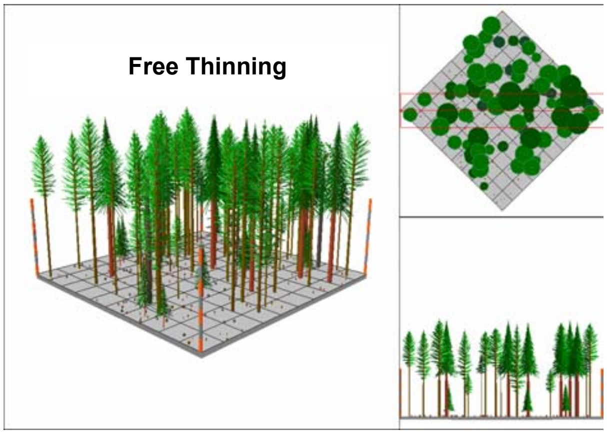

Figure 5. A 70-year old mixed conifer stand, showing the results of free thinning.

3.2 Quantifying Fire Hazard and Fire Potential

Accurate quantification of fuels in the canopy and shrub/small tree strata is necessary to understand the combustion environment of crown fire (Scott and Reinhardt 2001, Cruz et al. 2003). The most effective techniques for reducing crown fire occurrence and severity are those that (1) increase canopy base height, (2) reduce canopy bulk density (Agee 1996, Scott and Reinhardt 2001), (3) reduce forest canopy continuity (van Wagner 1977, Scott and Reinhardt 2001, Cruz et al. 2002), and (4) reduce surface fuels.

Objective and quantifiable fuel-treatment criteria will assist fire managers and silviculturists in achieving desired conditions for canopy base height, canopy bulk density, and canopy continuity (Scott and Reinhardt, in press). These criteria will depend on managers' assessments of potential fire behavior for specific fire weather, such as the 50th, 90th, and 98th percentile weather severity, or for moisture of 1-, 10-, and 100-hr timelag fuels (equivalent to fuel size classes of <0.25 in, 0.25-1.0 in, and 1.0-3.0 in, respectively). In addition, desired conditions must be adjusted for slope, because even greater fuel reductions are needed for steep slopes due to convective winds and heating, and increased fire intensity as fire spreads upslope.

Canopy base height should be considerably higher than the height of expected flame lengths for a specified fuelbed in order to avoid torching and crown fire initiation (Scott and Reinhardt 2001) (Figure 6). For most dry forests, this value will be >6 m (Jain et al. 2001). Using the flame length for the worst-case fire as a standard would be the least risky option. The required reduction in stem density and basal area will vary considerably between stands, depending on initial stem density and canopy structure. Target values of canopy base height can be inferred from canopy fuel descriptions for various forest types (Cruz et al. 2003; Reinhardt et al, see http://www firelab.org/fep/ research/canopy/canopy%20home.htm).

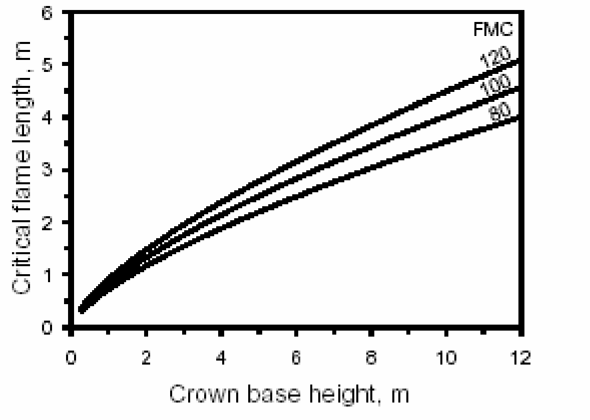

Figure 6. Critical flame length is less than crown base height when canopy base height is greater than about 1 m. The lines represent foliage moisture content of 80, 100, and 120%. From Scott and Reinhardt (2001).

Canopy bulk density should be maintained below a critical threshold (a function of fire weather and fire rate of spread) such that an active crown fire is not sustainable. This threshold is not well defined, although crown bulk density <0.10 kg m^{-3} appeared to be sufficient in the 1994 Wenatchee Fire in <100 year old ponderosa pine/Douglas-fir stands in the eastern Cascade Range of Washington (Agee 1996). The required reduction in stem density and basal area will vary considerably between stands, depending on initial stem density and canopy structure (Figure 7). For a ponderosa pine stand that has a dense understory and has not experienced fire for many decades, it may be necessary to remove 75% or more of the stems to achieve the target bulk density. Target values of canopy bulk density can be inferred from canopy fuel descriptions for various forest types (e.g., Cruz et al. 2003; Reinhardt et al., see http://www.firelab.org/fep/research/canopy/canopy%20home.htm.

Crown competition factor (total crown base area divided by stand area), which is correlated with canopy bulk density, may hold promise as a field measurement that represents crown fuels. For example, Jain et al. (2001) suggest that stands with a crown competition factor <140 have sufficiently low canopy densities to greatly reduce probability of crown fire. Additional empirical data are needed to determine how well this parameter works as a guideline for thinning.

Canopy continuity is difficult to quantify and is a subjective fuel treatment target. The general objective is to reduce physical contact of tree canopies and fire spread through the canopy. During extreme fire weather, fire spreads through horizontal and vertical heat flux and spotting from embers, so relatively wide spacing of canopies is necessary to reduce crown-fire hazard. An example of a field-based rule is that the distance between adjacent tree crowns should be half the average diameter of the crown of codominant trees in the stand.

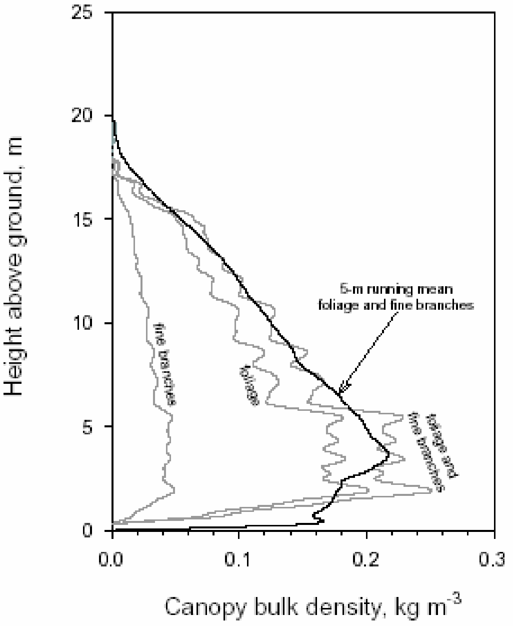

Figure 7. Vertical profile of canopy bulk density in a lodgepole pine (*Pinus contorta*) stand in Montana. In this case, effective canopy bulk density is considered to be the maximum 5-m running mean (0.21 kg m^{-3} in this stand). Canopy bulk density varies depending on species, stand age, and stem density. The vertical distribution shown in this example is typical of stands with high stem density and many understory trees. From Scott and Reinhardt (2001).

The Fuelbed Characteristics Classification System (FCCS) is another approach to characterizing fire hazard and developing fuel-treatment guidelines. The FCCS estimates quantitative fuel characteristics (physical, chemical and structural properties) and probable fire parameters from comprehensive or partial stand inventory data, and allows users to access existing fuelbed descriptions or create custom fuelbeds for any location in the United States (Sandberg et al. 2001). Indices of reaction potential, crown-fire potential, and fire-effects potential are computed from detailed inventory associated with each fuelbed. The FCCS contains empirical fuelbed data from throughout the United States compatible with stand inventory data used by silviculturists. The FCCS will be available online in early 2004.

4. ASSESSING LARGE-SCALE FUEL CONDITIONS

Effective fuel treatment programs must consider the spatial pattern of fuels across large landscapes (e.g., Hessburg et al. 2000), because multiple stands and fuel conditions are involved in large fires (Finney 2001). Fire behavior under extreme fire weather may involve large areas of fuels, multiple fires, and spotting, so a “firesafe” landscape needs to populate hundreds to thousands of hectares with strategically located fuel treatments (Finney 2003). Treating small or isolated stands without assessing the broader landscape will be ineffective in reducing wildfire extent and severity.

The efficacy of fuel treatments across large landscapes can be visualized with spatially explicit management tools such as the Landscape Management System (LMS), which automates stand projections and manipulations, summarizes stand-level attributes, and displays associated graphs and tables (McCarter et al. 1998). LMS uses stand inventory data (species, height, diameter, stem density), geospatial data, and forest growth models to project forest vegetation succession and changes in landscape pattern. All variants of the Forest Vegetation Simulator (FVS) (Crookston 1990, http://www.fs.fed.us/fmsc/fvs/description/ model.php) and ORGANON (Hann et al. 1997, http://www.col orst.edu/col/fr/research/ organon) are embedded within the system.

Silvicultural treatments can be implemented in LMS at designated times during a planning cycle (e.g. year projection)). Stand treatments include thinning to target basal area (BA), stand density index (SDI), or trees per acre (TPA). Thinning can be executed from above, below, proportionally or within specific diameter limits. The systems also have the ability to add new records (regeneration or ingrowth files). The effects of treatment can be readily analyzed with graphs, tables, and stand and landscape visualizations for any time period during the planning cycle.

LMS or another tool can be used to to display spatial patterns of forest structures and fuels across a landscape for existing conditions and compared to patterns produced by various fuel-treatment scenarios. Fuel conditions can be quantified with the FCCS, NFFL or NFDRS fuel models, or other fire-hazard indices. By scanning across spatial patterns, fire managers can determine priority areas for fuel treatments and identify blocks of stands that need treatment to achieve desired fuel conditions. Integrating basic landscape analysis with fuel-treatment prescriptions for specific stands will be the most effective approach for managing fuels and reducing crown-fire hazard at large spatial scales.

Simulation modeling can also be used to predict propagation of fire at broad spatial scales. FARSITE is the primary tool used to model fire spread, including crown fire, for forest landscapes (Finney 1998). This program integrates geospatial fuels data, climatic data, and fire behavior modeling (BEHAVE, Andrews 1986) to predict fire spread. Although FARSITE requires large databases, simulation modeling skill, and good computer resources, it is a powerful tool for simulating the spread of fire across large landscapes (e.g., Finney 2003), assuming that spatially explicit fuels data and good climatic data are available.

The use of a landscape analysis tool can also be effective in scheduling fuel treatments over time. For example, the FVS and the Fuel and Fire Effects extension of FVS (Reinhardt and Crookston, in press) can be used to quantify vegetation and fuel succession following fire or fuel treatments. By choosing a target for crown-fire hazard (e.g., a specific FCCS code or NFFL fuel model) above which hazard is deemed unacceptable, fuel treatments can be scheduled to always remain below the management threshold. Following initial thinning and prescribed burning to reduce high fuel accumulations, frequent prescribed burning (e.g., every 5-20 years) may be sufficient to control tree regeneration and surface fuels. If this is not desirable or practical, thinning can be scheduled at desired intervals, perhaps accompanied by prescribed fire, to reduce ingrowth of ladder fuels. Scheduling of fuel treatments will vary by species, elevation, aspect, climatic zone, and soil fertility.

5. COMPLEXITY AND UNCERTAINTY IN FUELS MANAGEMENT

Forest ecosystems are inherently complex entities about which we have only a basic scientific understanding. Detailed site-specific data on anything beyond basic forest structure and fuel properties are rare, limiting our analytical capability to prescribe management actions to achieve desired conditions for fuels and fire hazard. Fire behavior modeling is reasonable for surface fires but in its infancy for crown fires. Our understanding of the interaction of fuels, topography, and weather is poorly quantified for most ecosystems, especially under severe fire weather conditions in which chaotic and unpredictable phenomena may prevail. In the face of this complexity, it is important to focus on basic principles that will assist decision making and guide future data collection (Table 2).

Table 2. Principles of fire-resilient forests (adapted from Agee 2002b).

Objective	Effect	Advantage	Concerns
Reduce surface fuels	Reduces potential flame length	Fire control easier, less torching	Surface disturbance less with fire than other techniques
Increase canopy base height	Requires longer flame length to begin torching	Less torching	Opens understory, may allow surface wind to increase
Decrease crown density	Makes independent crown fire less probable	Reduces crown fire potential	Surface wind may increase, surface fuels may be drier
Retain larger trees	Thicker bark, taller crowns, higher canopy base height	Increases survivability of trees	Removing smaller trees is economically less profitable

Stakeholders in the current effort to develop strategies for managing fuels on forest lands in the United States must be aware of the uncertainty associated with management decisions based on an incomplete scientific database. This uncertainty may be important for decisions about treatments in forests adjacent to structures and local communities, but relatively unimportant in forests adjacent to a wilderness area.

One approach is to target desired fuel conditions that will achieve a specific fire hazard or predicted fire behavior outcome for specific fire weather severity. But even this approach has a great deal of uncertainty because of the unpredictability of fire during extreme fire weather.

The relationship between specific fuel treatments (e.g., thinning and prescribed burning) and wildfires is based on a limited empirical database and has yet to be quantified accurately. Some types of thinning and subsequent residue treatment can be effective at reducing crown fire hazard, whereas others can exacerbate fire hazard. Good quantitative guidelines will probably not be available for another decade or more, so resource managers will need to use the best information available and expert opinion, and clearly state the level of risk they are willing to accept on any particular forest stand or landscape.

6. REFERENCES

Agee, J.K. 1991. Fire history along an elevational gradient in the Siskiyou Mountains, Oregon. *Northwest Science* 65:188-199.

Agee, J.K. 1993. *Fire Ecology of Pacific Northwest Forests*. Island Press, Washington, DC.

Agee, J.K. 1994. Fire and weather disturbances in terrestrial ecosystems of the eastern Cascades. USDA Forest Service General Technical Report PNW-GTR-320. Pacific Northwest Research Station, Portland, OR.

Agee, J.K. 1996. The influence of forest structure on fire behavior. In: *Proceedings, 17th Annual Forest Vegetation Management Conference*. January 16-18, 1996: Redding, California. Pp. 52-68.

Agee, James, Berni Bahro, Mark Finney, Philip Omi, David Sapsis, Carl Skinner, Jan van Wagtendonk and C. Phillip Weatherspoon. 2000. The use of shaded fuelbreaks in landscape fire management. Forest Ecology and Management 127 Issues 1-3:55-66.

Agee, J.K. 2002. Fire behavior and fire-resilient forests. In S. Fitzgerald (ed.), *Fire in Oregon's Forests: Risks, Effects, and Treatment Options*. Oregon Forest Resources Institute, Portland, OR. Pp. 119-126.

Agee et al. 2000. xx

Albini, F., and R.G. Baughman. 1979. Estimating windspeeds for predicting wildland fire behavior. USDA Forest Service Research Paper INT-221. Intermountain Forest and Range Experiment Station, Ogden, UT.

Allen, C.D., M. Savage, D.A. Falk, K.F. Suckling, T.W. Swetnam, T. Schulke, P.B. Stacey, P. Morgan, M. Hoffman, and J.T. Klingel. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. *Ecological Applications* 12:1418-1433.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. National Wildfire Coordinating Group General Technical Report INT-122.

Andrews, P.L. 1986. BEHAVE: fire behavior prediction and fuel modeling system – BURN subsystem, part 1. USDA Forest Service Intermountain Forest and Range Experiment Station General Technical Report INT-194. Ogden, UT.

Arno, S.F. 1980. Forest fire history of the northern Rockies. *Journal of Forestry* 78:460-465.

Arno, S.F., and J.K. Brown. 1991. Overcoming the paradox in managing wildland fire. *Western Wildlands* 171:40-46.

Arno, S.F., and S. Allison-Bunnell. 2002. *Flames in our Forest: Disaster or Renewal?* Island Press, Washington, DC.

Baisan, C.H. and T.W. Swetnam. 1997. Interactions of fire regimes and land use in the central Rio Grande Valley. USDA Forest Service Research Paper RM-RP-330. Rocky Mountain Research Station, Fort Collins, CO.

Biswell, H.H. 1960. Danger of wildfire reduced by prescribed burning in ponderosa pine. *California Agriculture* 1410:5-6.

Bonnicksen, T.M., and E.P. Stone. 1982. Reconstruction of a pre-settlement giant sequoia/mixed conifer forest community using the aggregation approach. *Ecology* 63: 1134-1148.

Carey, H., and M. Schuman. 2003. Modifying wildfire behavior – the effectiveness of fuel treatments: the status of our knowledge. National Community Forestry Center, Southwest Region Working Paper 2. (http://www.theforesttrust.org/images/swcenter/pdf/workingpaper2.pdf)

Cooper, C.F. 1960. Changes in vegetation, structure and growth of southwestern pine forest since white settlement. *Ecological Monographs* 30:129-164.

Crookston, N.L. 1990. User's guide to the event monitor: part of Prognosis Model, version 6. USDA Forest Service General Technical Report INT-GTR-275. Intermountain Forest and Range Experiment Station, Ogden, UT.

Cruz, M.G., M.E. Alexander, and R.H. Wakimoto. 2002. Predicting crown fire behavior to support forest fire management decision-making. In: *Forest Fire Research and Wildland Fire Safety*. Millpress, Rotterdam, p. 1-10.

Cruz, M.G., M.E. Alexander, and R.H. Wakimoto. 2003. Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. *International Journal of Wildland Fire* 12: 39-50.

Dodge, M. 1972. Forest fuel accumulation – a growing problem. *Science* 177:139-142.

Finney, M.A. 1998. FARSITE: Fire Area Simulator – model development and evaluation. USDA Forest Service Research Paper RMRS-RP-4. Rocky Mountain Research Station, Fort Collins, CO.

Finney, M.A. 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. *Forest Science* 47:219-228.

Finney, M.A. 2003. Calculation of fire spread rates across random landscapes. International Journal of Wildland Fire 12:167-174.

Fitzgerald, S.A. 2002. Fuel-reduction and restoration tredatments for Oregon's forests. In S. Fitzgerald (ed.), *Fire in Oregon's Forests: Risks, Effects, and Treatment Options*. Oregon Forest Resources Institute, Portland, OR. Pp. 127-138.

Fulé, P.Z., W.W. Covington, and M.M. Moore. 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine. *Ecological Applications* 7:895-908.

Graham, R.T. 2002. Executive summary, interim Hayman Fire case study analysis. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Graham, R.T., A.E. Harvey, T.B. Jain, and J.R. Tonn. 1999. The effects of thinning and similar stands treatments on fire behavior in western forests. USDA Forest Service General Technical Report PNW-GTR-463. Pacific Northwest Research Station, Portland, OR.

Hann, D.W., A.S. Hester, and C.L. Olsen. 1997. ORGANON user's manual: edition 6. Department of Forest Resources, Oregon State University, Corvallis, OR.

Hessburg, P.F., B.G. Smith, R.B. Salter, R.D. Ottmar, and E. Alvarado. 2000. Recent changes (1930s-1990s) in spatial patterns of interior Northwest forests, USA. *Forest Ecology and Management* 136:53-83.

Hessl, A.E., D. McKenzie, and R. Schellhaas. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. *Ecological Applications*. In press.

Huff, M.H., R.D. Ottmar, E. Alvarado, R.E.Vihnanek, and J.F. Lehmkuhl, and P.F. Hessburg, and R.L. Everett. 1995. Historical and current forest landscapes in eastern Oregon and Washington. Part II. Linking vegetation characteristics to potential fire behavior and smoke production. USDA Forest Service General Technical Report PNW-GTR-355. Pacific Northwest Research Station, Portland, OR.

Jain, T.B., D.E. Ferguson, R.T. Graham, and others. 2001. Influence of forest structure on wildfire burn severity: a retrospective look. Study plan on file with USDA Forest Service, Rocky Mountain Research Station, Moscow, ID.

Kalabokidis, K.D., S. Gatzojannis, and S. Galatsidas. 2002. Introducing wildfire into forest management planning: towards a conceptual approach. *Forest Ecology and Management* 158:41-50.

Kalabokidis, K.D. and P.N. Omi. 1998. Reduction of fire hazard through thinning/residue disposal in the urban interface. International *Journal of Wildland Fire* 7:29-35.

Laudenslayer, W.F., H.H. Darr, and S. Smith. 1989. Historical effects of forest management practices on eastside pine communities in northeastern California. In A. Tecle, W.W. Covington, and R.H. Hamre (technical coordinators), Multiresource management of ponderosa pine forests: Proceedings of the symposium; 1989 November 14-16; Flagstaff, AZ. USDA Forest Service General Technical Report RM-185. Rocky Mountain Research Station, Fort Collins, CO. Pp. 26-34.

MacCleery, D.W. 1995. The way to a healthy future for national forest ecosystems in the West: what role can silviculture and prescribed fire play? USDA Forest Service General Technical Report RM-267. Rocky Mountain Research Station, Fort Collins, CO. Pp. 37-45.

McCarter, J.M., J.S. Wilson., P.J. Baker., J.L. Moffett, and C.D. Oliver. 1998. Landscape management through integration of existing tools and emerging technologies. *Journal of Forestry* 96:17-23.

McLean, H.E. 1993. The Boise quickstep. *American Forests* 99: 11-14.

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 Forest Service General Technical Report PNW-GTR-310. Pacific Northwest Research Station, Portland, OR.

Parsons, D.J., and S. DeBenedetti. 1979. Impact of fire suppression on a mixed-conifer forest. *Forest Ecology and Management* 2:21-33.

Pollet, J., and P.N. Omi. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire* 11:1-10.

Quigley, T.M., R.W. Haynes, and R.T. Graham. 1996. Integrated scientific assessment for ecosystem management in the interior Columbia Basin. USDA Forest Service General Technical Report GTR-PNW-382. Pacific Northwest Research Station, Portland, OR.

Reinhardt, E.D., and N.L. Crookston (eds.). The Fire and Fuels Extension to the Forest Vegetation Simulator. USDA Forest Service General Technical Report GTR-RM-xxx. Rocky Mountain Research Station, Ogden, UT. In press.

Rothermel, R.C. 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. USDA Forest Service Intermountain Research Station Research Paper INT-438. Ogden, UT.

Sandberg, D.V., R.D. Ottmar, and G.H. Cushon. 2001. Characterizing fuels in the 21st century. *International Journal of Wildland Fire* 10:381-387.

Schmidt, K.M., J.P. Menakis, C.C. Hardy, W.J. Hann, and D.L. Bunnell. 2002. Development of coarse-scale spatial data for wildland fire and fuel management. USDA Forest Service General Technical Report RMRS-GTR-87. Rocky Mountain Research Station, Fort Collins, CO.

Schmoldt, D.L., D.L. Peterson, R.E. Keane, J.M. Lenihan, D. McKenzie, D.R. Weise, and D.V. Sandberg. 1999. Assessing the effects of fire disturbance on ecosystems: a scientific agenda for research and management. USDA Forest Service Pacific Northwest Research Station General Technical Report GTR-PNW-455. Portland, OR.

Scott, J.H., and E.D. Reinhardt. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. USDA Forest Service Rocky Mountain Research Station Research Paper RMRS-RP-29.

Fort Collins, CO.

Scott, J.H., and E.D. Reinhardt. NEXUS: a spreadsheet-based crown fire hazard assessment system. In Proceedings on Fire in California Ecosystems. USDA Forest Service General Technical Report GTR-PSW-xxx. Pacific Southwest Research Station, Albany, CA. In press.

Skinner, C.N. 2003. Presentation at Joint Fire Science Program workshop, Phoenix, AZ, March 2003.

Skinner, C. N., and C. Chang. 1996. Fire regimes, past and present. In *Sierra Nevada Ecosystem Project: Final Report to Congress*, vol. II chap. 38. University of California, Centers for Water and Wildland Resources, Davis.

Smith, D.M., B.C. Larson, M.J. Kelty, and P.M.S. Ashton. 1997. *The Practice of Silviculture: Applied Forest Ecology*. 9th edition. John Wiley and Sons, New York.

Strauss, D., L. Bednar, and R. Mees. 1989. Do one percent of forest fires cause ninety-nine percent of the damage? *Forest Science* 35:319-328.

Swetnam, T.W., C.D. Allen, and J.L. Betancourt. 1999. Applied historical ecology: using the past to manage for the future. *Ecological Applications* 9:1189-1206

Taylor, A.H., and C.N. Skinner. 1998. Fire history and landscape dynamics in a late-successional reserve, Klamath Mountains, California USA. *Forest Ecology and Management* 111: 285-301.

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

Weatherspoon, C.P. 1996. Fire-silviculture relationships in Sierra forests. *Sierra Nevada Ecosystem Project: Final Report to Congress*, Vol II, Assessments and scientific basis for management options. Centers for Water and Wildland Resources, University of California, Davis.

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.