Forest Structure and Fire Hazard in Dry Forests of the Western United States

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Abstract

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Fire, in conjunction with landforms and climate, shapes the structure and function of forests throughout the Western United States, where millions of acres of forest lands contain accumulations of flammable fuel that are much higher than historical conditions owing to various forms of fire exclusion. The Healthy Forests Restoration Act mandates that public land managers assertively address this situation through active management of fuel and vegetation. This document synthesizes the relevant scientific knowledge that can assist fuel-treatment projects on national forests and other public lands and contribute to National Environmental Policy Act (NEPA) analyses and other assessments. It is intended to support science-based decisionmaking for fuel management in dry forests of the Western United States at the scale of forest stands (about 1 to 200 acres). It highlights ecological principles that need to be considered when managing forest fuel and vegetation for specific conditions related to forest structure and fire hazard. It also provides quantitative and qualitative guidelines for planning and implementing fuel treatments through various silvicultural prescriptions and surface-fuel treatments. Effective fuel treatments in forest stands with high fuel accumulations will typically require thinning to increase canopy base height, reduce canopy bulk density, reduce canopy continuity, and require a substantial reduction in surface fuel through prescribed fire or mechanical treatment or both. Long-term maintenance of desired fuel loadings and consideration of broader landscape patterns may improve the effectiveness of fuel treatments.

Keywords: Crown fire, fire hazard, forest structure, fuel treatments, prescribed burning, silviculture, thinning.

Preface

This document is part of the Fuels Planning: Science Synthesis and Integration Project, a pilot project initiated by the U.S. Forest Service to respond to the need for tools and information useful for planning site-specific fuel (vegetation) treatment projects. The information primarily addresses fuel and forest conditions of the dry inland forests of the Western United States: those dominated by ponderosa pine, Douglas-fir, dry grand fir/white fir, and dry lodgepole pine potential vegetation types. Information, other than social science research, was developed for application at the stand level and is intended to be useful within this forest type regardless of ownership. Portions of the information also will be directly applicable to the pinyon pine/juniper potential vegetation types. Many of the concepts and tools developed by the project may be useful for planning fuel projects in other forest types. In particular, many of the social science findings would have direct applicability to fuel planning activities for forests throughout the United States. As is the case in the use of all models and information developed for specific purposes, our tools should be used with a full understanding of their limitations and applicability.

The science team, although organized functionally, worked hard at integrating the approaches, analyses, and tools. It is the collective effort of the team members that provides the depth and understanding of the work. The science team leadership included Deputy Science Team Leader Sarah McCaffrey (USDA FS, North Central Research Station); forest structure and fire behavior—Dave Peterson and Morris Johnson (USDA FS, Pacific Northwest Research Station); environmental consequences—Elaine Kennedy-Sutherland and Anne Black (USDA FS, Rocky Mountain Research Station); economic uses of materials—Jamie Barbour and Roger Fight (USDA FS, Pacific Northwest Research Station); public attitudes and beliefs—Pam Jakes and Sue Barro (USDA FS, North Central Research Station); and technology transfer—John Szymoniak, (USDA FS, Pacific Southwest Research Station).

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Summary

The structure and fuel loading of many dry forests in the Western United States have changed considerably during the past century. Fire exclusion, forest harvest, and various land use practices have reduced the frequency of fires, especially in low-severity fire regimes, resulting in high accumulations of canopy and surface fuel. When fires occur in these stands now, the potential for crown fires and large fires is greater than in presettlement times. Public policy asserts that managers of national forests and other public lands need to accelerate the treatment of hazardous fuel and reduce crown-fire hazard, while maintaining sustainable forest ecosystems that provide desired resources and values.

This document synthesizes the relevant scientific knowledge that can assist fuel-treatment projects on national forests and other public lands at the scale of forest stands (about 1 to 200 acres). It supports science-based decisionmaking for fuel management and ecological restoration in dry forests, and it can contribute to National Environmental Policy Act (NEPA) analyses and other assessments that need to consider the effects of fuel treatments on fire hazard and natural resources. To date, there have been few guidelines that explicitly link alteration of stand structure and canopy fuel with potential fire behavior and fire effects. This document provides the scientific basis for applying quantitative and qualitative guidelines to modify stand density, canopy base height, canopy density, and surface-fuel loadings.

The scientific basis for using thinning and surface-fuel treatments (prescribed burning, manual and mechanical changes in fuel) to reduce crown-fire hazard is explored, as well as evidence for fuel-treatment effectiveness in large fires, and the role of extreme weather in fire landscapes. In forest stands that have not experienced fire or thinning for several decades, heavy thinning combined with (often multiple) prescribed-fire or other surface-fuel treatments, or both, is necessary to effectively reduce potential fire behavior and crown-fire hazard. Prescriptions for treating individual stands should be developed in the context of fuel conditions across the broader landscape, so that effective spatial patterns of reduced fuel can be maintained over decades. Until more empirical data on the effectiveness of fuel treatments in reducing fire behavior and fire effects in large fires are available, the following scientific principles can be used to guide decisionmaking: (1) reduce surface fuel, (2) increase canopy base height, (3) reduce canopy density, and (4) retain larger trees.

Objective

This document is a synthesis of scientific knowledge that can assist fuel-treatment projects on national forests and other public lands. It is intended to support science-based decisionmaking for fuel and vegetation management in dry forests of the Western United States at the scale of forest stands (about 1 to 200 acres). By synthesizing key scientific information related to the effects of forest structure on fire hazard and potential fire behavior, it highlights ecological principles that need to be considered when managing forest fuel and vegetation for specific conditions related to fire hazard. It also provides quantitative and qualitative guidelines for planning and implementing fuel treatments. This scientific information is needed by resource managers and planners for inclusion in National Environmental Policy Act (NEPA) analyses and other documents that need to consider a range of alternative fuel treatments.

There are many related topics that must be considered when making decisions about fuel treatments, such as economic analysis, social implications, risks and tradeoffs, and effects of various fuel treatments on sensitive species, wildlife, soil, and hydrology. These topics are, for the most part, not considered here but are addressed in other scientific literature.

Background

Millions of acres of forest lands in the Western United States contain accumulations of flammable fuel that are much higher than historical conditions. Forest fuel conditions have increased fire hazard over several decades, the result of fire suppression (Covington and Moore 1994), livestock grazing (Savage and Swetnam 1990), timber harvest, and farm abandonment (Arno et al. 1997). The large wildfires in the summers of 2000 and 2002 have sharpened our focus on fuel accumulation on national forests and other public lands. During the summer of 2000, 122,827 wildfires burned 8.4 million acres in the United States, and during the summer of 2002, 88,458 fires burned 6.9 million acres (USDI BLM 2004).

Managers and policymakers seek a strategy capable of reducing the size and severity (damage to the forest overstory and associated changes in resource value) of wildfires in the future. The Healthy Forests Restoration Act of 2003 (HFRA 2003), National Fire Plan (USDA USDI 2001), and the 10-Year Comprehensive Strategy Implementation Plan (USDA USDI 2002) highlight the need for fuel reduction in Western forests. Although the scope of work and the available tools are described in these documents, little guidance on specific stand and landscape target conditions is provided. The Joint Fire Science Program and the research component of the National Fire Plan focus on scientific principles and tools to support decisionmaking and policy about fuel treatments.

Fire, in conjunction with landforms and climate, shapes the structure and function of forests throughout the Western United States (Agee 1998, Schmoldt et al. 1999), from wet coastal forests to cold subalpine forests to arid interior forests. Climatic patterns, especially magnitude and distribution of precipitation, influence the spatial and temporal distribution of wildfires (Hessl et al. 2004, Heyerdahl et al. 2001). Alteration of fire regimes by fire exclusion has likely been greatest in arid to semiarid forests of the Western United States, primarily forests dominated by ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), Douglas-fir

(*Pseudotsuga menziesii* [Mirb.] Franco) or both, which formerly had more frequent fires than today (e.g., Everett et al. 2000).

Prior to the 20th century, low-intensity fires burned regularly in many arid to semiarid forest ecosystems, with ignitions caused by lightning and humans (e.g., Allen et al. 2002, Baisan and Swetnam 1997). Low-intensity fires controlled regeneration of fire-sensitive species (e.g., grand fir [*Abies grandis* (Dougl. ex D. Don) Lindl.]) (Arno and Allison-Bunnell 2002), promoted fire-tolerant species (e.g., ponderosa pine, Douglas-fir, western larch [*Larix occidentalis* Nutt.]), and maintained a variety of forest structures including a higher proportion of low-density stands than currently exists (Swetnam et al. 1999). These fires reduced fuel loading and maintained wildlife habitat for species that require open stand structure. Lower density stands likely had higher general vigor and lesser effects from insects (Fulé et al. 1997, Kalabokidis et al. 2002). In many areas, fire exclusion has caused the accumulation of understory vegetation and fuel, greater continuity in vertical and horizontal stand structure, and increased potential for crown fires (Agee 1993, Arno and Brown 1991, Dodge 1972, van Wagner 1977). Across any particular landscape, there were probably a variety of stand structures, depending on local climate, topography, slope, aspect, and elevation.

Most fire history data and much of our understanding of fire in the West are from forests with low-severity (high-frequency) fire regimes. These forests are the ones whose (increased) fuels and (decreased) fire frequency have changed the most during the past century. The concept of Fire Regime Condition Class (sensu Schmidt et al. 2002) uses current fuel conditions to represent the degree of departure from historical fire regimes and fuel conditions at a broad spatial scale. As a result, many arid and semiarid forests that historically were in Condition Class 1 are now in Condition Class 2 or 3: fires were frequent and low severity in the past, but they now have greater potential to be both large and severe. Extreme fire weather is associated with large fires in subalpine forests of the southern Canadian Rocky Mountains (Bessie and Johnson 1995) and the American Rockies (Romme and Despain 1989), and these types of forests with high-severity (low-frequency) fire regimes have probably not changed much. Forests with mixed-severity (moderate-frequency) fire regimes may have changed somewhat, but not as much as forests with low-severity regimes.

Approximately 59 percent 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 about 43 percent of Fire Regime 2 forests have higher fuel accumulations (currently Condition Class 3) than they would have historically (Schmidt et al. 2002). For example, in the inland Northwestern United States, forests that would currently burn with high severity compose 50 percent of the forest landscape compared to only 20 percent historically (Quigley et al. 1996) (fig. 1). If these general relationships are applied to regional and local situations, then they need to be refined with site-specific information.

Changes in Forest Structure

Vertical arrangement and horizontal continuity of many arid and semiarid low-elevation forests in the Western United States differ from historical stand structures (Carey and Schumann 2003,

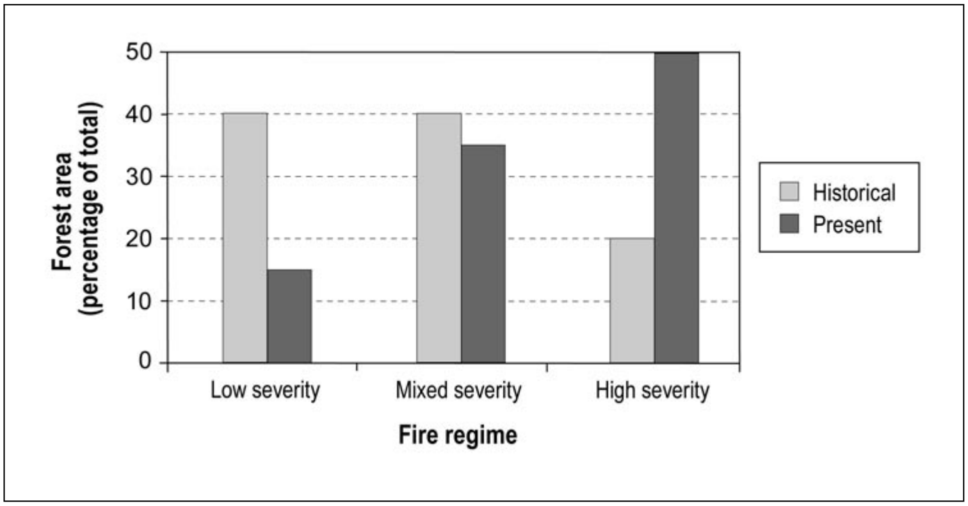

Figure 1—The proportion of low-severity, mixed-severity, and high-severity fire regimes in the pre-1900 (historical) period and in recent times in the inland Northwestern United States. Note the increasing proportion of high-severity fire regime. (From Quigley et al. 1996)

Mutch et al. 1993) (fig. 2). Current forests have denser canopies, a higher proportion of fire-intolerant species, and fewer large trees (Bonnicksen and Stone 1982, Parsons and DeBenedetti 1979).

These conditions increase the probability of surface fires developing into crown fires, because understory ladder fuels lower the effective canopy base height (lowest height above ground at which there is significant canopy fuel to propagate fire vertically through the canopy [Scott and Reinhardt 2001]) of the stand (Laudenslayer et al. 1989, MacCleery 1995). This departure from historical conditions is common in high-frequency, low- to moderate-severity fire regimes (Agee 1991, 1993, 1994; Arno 1980; Skinner and Chang 1996; Taylor and Skinner 1998). Historical observers (e.g., Weaver 1943) described Western forest structures as open with minimum understory vegetation, a condition largely maintained by frequent, low-intensity surface fires.

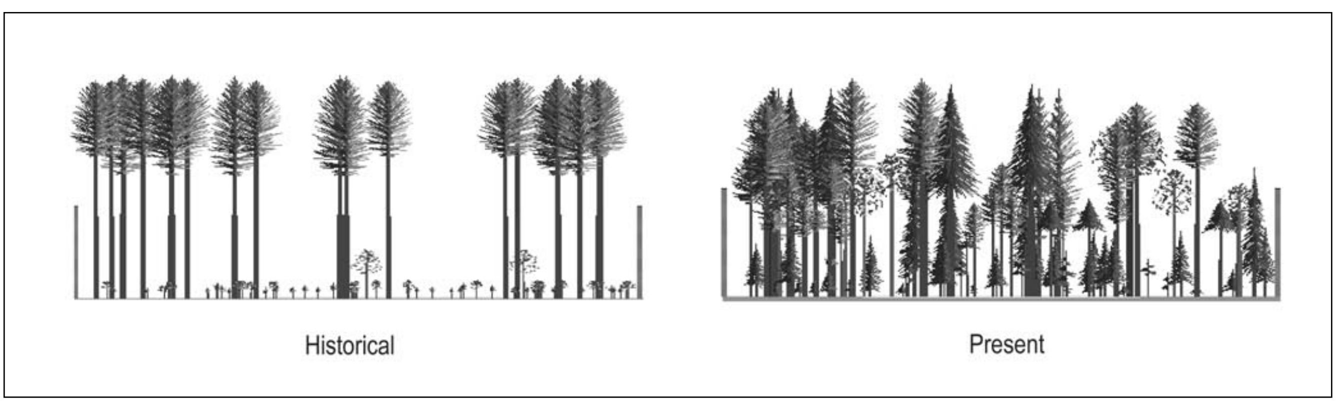

Figure 2—Representation of changes in vertical arrangement and horizontal continuity in forest stand structure. Today's forests tend to have more fuel strata, higher densities of fire-sensitive species and suppressed trees, and greater continuity between surface and crown fuel.

Fuel, Fire Behavior, and Fire Effects

Fuel, topography (or physical setting), and **weather** interact to create a particular fire intensity (energy release, flame length, rate of spread) and severity. Although much of this document focuses on the effects of forest structure on fire hazard and behavior, decisions about fuel treatment must also consider topography and weather, which influence fire at different spatial scales. The forest structure needed to achieve a specific fuel condition for a particular location will differ depending on slope, aspect, and elevation, and on temperature, humidity, and windspeed.

Stand structure and wildfire behavior are clearly linked (Biswell 1960, Cooper 1960, Dodge 1972, McLean 1993, Rothermel 1991, van Wagner 1977), so fuel-reduction treatments are a logical approach to reducing extreme fire behavior. The principal goal of fuel-reduction treatments is to reduce fireline intensities (heat release per unit distance per unit time), reduce the potential for crown fires, improve opportunities for successful fire suppression, and improve the ability of forest stands to survive wildfire (Agee 2002a). Prescribed fire can be implemented under benign weather to reduce surface fuel and fireline intensity. Silvicultural treatments that target canopy bulk density (the foliage mass contained per unit crown volume), canopy base height, and canopy closure have the potential to reduce the development of all types of crown fires (Cruz et al. 2002, Rothermel 1991, Scott and Reinhardt 2001, van Wagner 1977) if surface fuels are relatively low or are concurrently treated.

Fire hazard for any particular forest stand or landscape is 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) forest canopy; (2) shrubs/small trees; (3) low vegetation; (4) woody fuel; (5) moss, lichens, and litter; and (6) ground fuel (duff) (Sandberg et al. 2001) (fig. 3). Each of these strata can be divided into separate categories based on physiognomic characteristics and relative abundance. Modification of any fuel stratum has implications for fire behavior, fire suppression, and fire effects (fig. 4).

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 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 fuel" that provides continuity from the surface fuel to canopy fuel, thereby potentially facilitating active crown fires.

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**

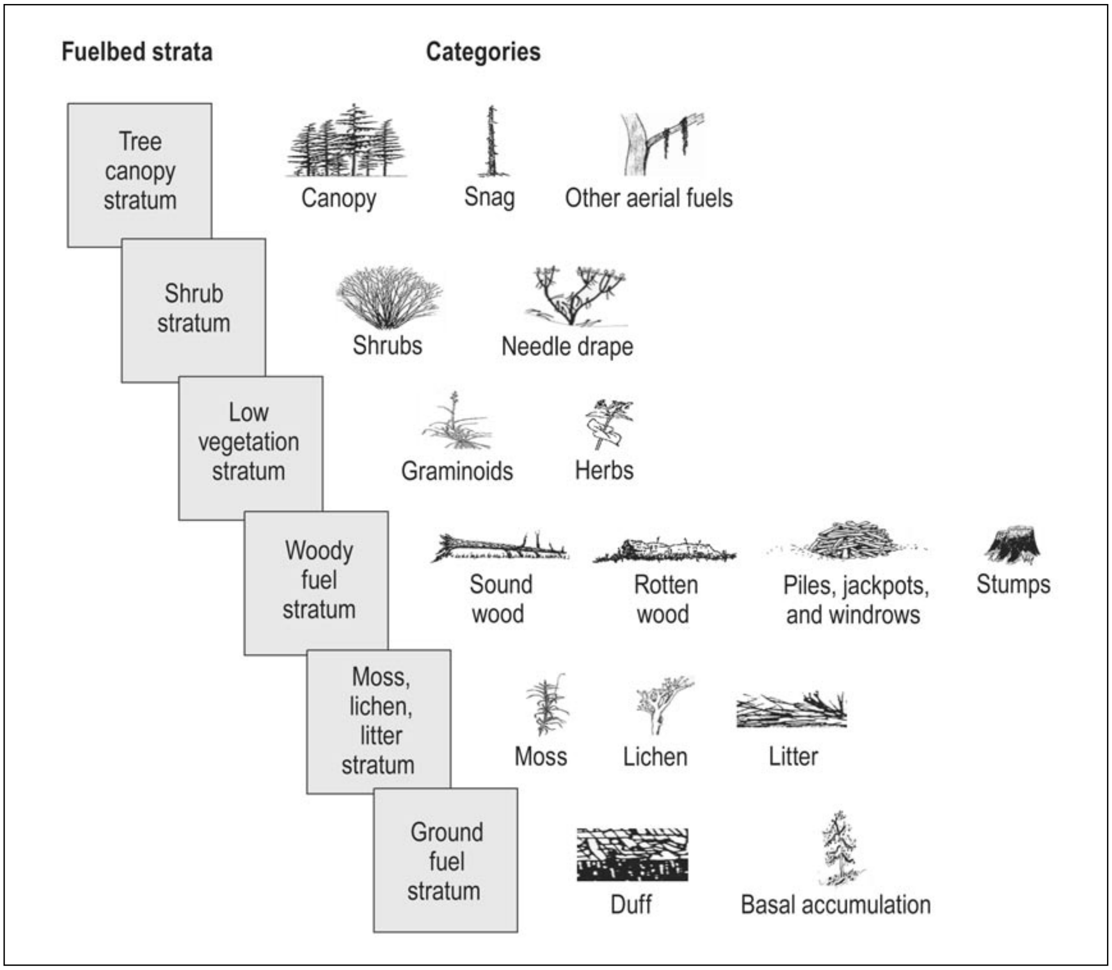

Figure 3—Six horizontal fuelbed strata represent unique combustion environments. Each fuelbed category is described by morphological, chemical, and physical features and by relative abundance. (From Sandberg et al. 2001)

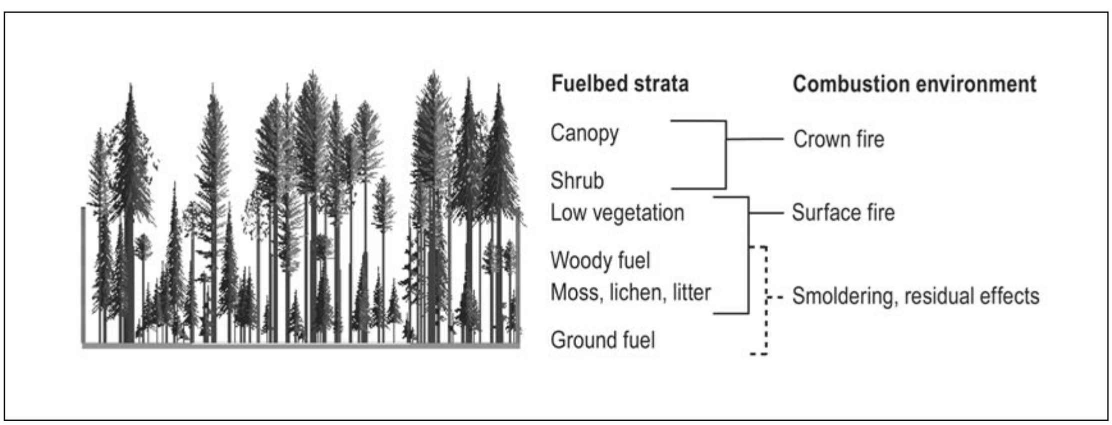

Figure 4—Fuelbed strata affect the combustion environment, fire propagation and spread, and fire effects. Note that woody surface fuel can also contribute to crown fires.

crown fires, which are much less common than passive or active crown fires, burn canopy fuel 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 release enough energy to preheat and combust fuel well above the surface (Agee 2002b). 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 (Agee et al. 2000, van Wagner 1977). Torching occurs when the surface flame length exceeds a critical threshold defined by moisture content of fuel in the canopy and by canopy base height (Scott and Reinhardt 2001, van Wagner 1977). Foliage moisture varies within a tree, with newer foliage generally having higher moisture than older foliage, and varies greatly during the course of a year, depending on the local climatic regime.

The canopy base height, defined as the lowest height above which at least 30 $lb \cdot ac^{-1} \cdot ft^{-1}$ of available canopy fuel is present (Scott and Reinhardt 2001), determines how critical the moisture factor can become. For example, if foliage moisture averages 100 percent in late summer, a canopy base height of 7 ft means any surface fire with a flame length exceeding 4.5 ft would likely produce torching. If the bottom of the crown is lifted to 20 ft, the predicted critical flame length would be 9 ft, so a much more intense surface fire would be needed to initiate a crown fire (Scott and Reinhardt 2001).

Active crown-fire spread begins with torching but is sustained by the density of the overstory canopy and fire rate of spread. Crown fire is unlikely below a specific rate of canopy fuel consumption. This rate is defined as a function of crown-fire rate of spread and canopy bulk density (van Wagner 1977). Where empirical rates of spread from observed crown 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 2002b).

To reduce the probability of crown fire, fuel-treatment planners should consider how canopy base height, canopy bulk density, and continuity of tree canopies affect the initiation and propagation of crown fire. As noted above, canopy base height is important because it affects crown-fire initiation. It is difficult to assess in the field because of the subjectivity of its location in a given forest stand, making it difficult for even experienced fire managers to quantify it with precision. This parameter has been accurately quantified in only a few forest stands in the United States and is difficult to assess because of the intensive nature of data collection required to quantify it. Continuity of canopy can encompass different properties related to the adjacency of tree crowns, but clearly, horizontal patchiness of the canopy will reduce the spread of fire within the canopy stratum.

Our understanding of crown fire, especially under severe fire weather conditions, is relatively poor owing to the complexity of interactions between fuel, topography, and local weather. Although many of the principles of crown-fire spread might appear to be similar across forest types, few experimental data on crown-fire spread for dry Western forests exist. For example, foliage moisture and foliage energy content affect crown-fire characteristics but are rarely quantified or included in fire behavior models (Williamson and Agee 2002). Even the basic measurement of canopy base height differs between different sources (e.g., Cruz et al. 2003, Scott and Reinhardt 2001) and is difficult to measure on the ground. In addition, understory shrubs are typically not included in calculation of canopy bulk density, although they are included in fire behavior simulation models such as BEHAVE (Andrews 1986). As a result, predictions of torching and crown-fire spread should be considered general estimates until we have a better empirical and conceptual basis for quantifying and modeling crown fire.

Surface fires were much more common in Western arid to semiarid forests prior to the 20th century (e.g., Everett et al. 2000). Three fuelbed strata contribute to the initiation and spread of surface fires (fig. 3). **Low vegetation**, consisting of grasses and herbs, can carry surface fires when that vegetation is dead or has low moisture content. The contribution of low vegetation to the combustion environment differs greatly between forest systems. **Woody fuel** can consist of sound logs, rotten logs, stumps, and wood piles from either natural causes or management activities. Wood can greatly increase the energy release component from surface fires and can in some cases increase flame lengths sufficiently to ignite ladder fuel and canopy fuel. **Moss, lichens, and litter** on the forest floor can also increase energy release in surface fuel. These fuel categories differ greatly among forest systems; e.g., dead needle litter is important in Southwestern ponderosa pine forests, whereas large accumulations of moss (live and dead) are important in Alaskan boreal forests. Because of the potential for surface fires to propagate into crown fires—even if tree density and crowns have been greatly reduced—treatment of surface fuel must be planned in conjunction with treatment of ladder fuel and crown fuel.

Surface fires are highly variable depending on surface-fuel packing, bulk densities, and size-class distributions. Surface fires burn in both flaming and postfrontal phases. Energy release rate is high during the short flaming phase in which fine fuels are consumed, and low during longer glowing and smoldering periods that consume larger fuels. Fine fuels such as grass typically have shorter flaming residence times than large woody materials such as logging slash.

Smoldering fires, also referred to as ground fires or residual smoldering, are an important but often overlooked component of most fires. Three fuelbed strata contribute to the initiation and slow spread of smoldering fires (fig. 3). **Ground fuel**, consisting principally of soil organic horizons (or duff) contributes most of the fuel, and can burn slowly for days to months if fuel moisture is sufficiently low. Deep layers of continuous ground fuel are often found in forests that have not experienced fire for several decades, with large additional accumulations near the bases of large trees. **Moss, lichens, and litter** have high surface area and when very dry can facilitate both the spread of smoldering fires and a transition to surface (flaming) fires. **Woody fuel** (sound logs, rotten logs, stumps, and wood piles) is often underestimated as a component of smoldering fire, but can sustain low-intensity burning for weeks to months, with potential flaming combustion under dry, windy conditions. Woody fuel also can contribute significantly to smoke production and soil impacts.

Each fuelbed and combustion environment is associated with different fire effects. **Crown fires** remove much or all of the tree canopy in a particular area, essentially resetting the successional and growth processes of a stand. These fires typically, but not always, kill or temporarily reduce the abundance of understory shrubs and trees. Crown fires have the largest immediate and long-term ecological effects and the greatest potential to threaten human settlements near wildland areas. **Surface fires** have the important effect of reducing low vegetation; woody; and moss, lichens, and litter strata. This temporarily reduces the likelihood of future surface fires propagating into crown fires. **Smoldering fires** that consume large amounts of woody fuel and the organic soil horizon can produce disproportionately large amounts of smoke. Ground fires reduce the accumulation of organic matter and carbon storage, and contribute to smoke production during active fires and long after flaming combustion has ended. Smoldering fires can also damage and kill large trees by killing their roots and the lower stem cambium. Because smoldering fires are often of long duration, they may result in greater soil heating than surface or crown fires, and have the potential for reducing organic matter, volatilizing nitrogen, and creating a hydrophobic layer that contributes to erosion.

Topography influences fire behavior at different spatial scales (Albini 1976, Chandler et al. 1983). Rate of spread doubles from 0- to 30-percent slope, and doubles again from 30- to 60-percent slope. Rate of spread on a 70-percent slope can be up to 10 times the rate on level ground. A narrow v-shaped canyon can radiate heat to adjacent slopes, drying fuels ahead of the active fire and leading to faster rate of spread. Local discontinuities such as ridges can create turbulence that affects rate of spread and energy release. Topography in conjunction with the general direction of fire spread and wind also affects fireline intensity and effects. **Head fires** (in the same direction as the main active fire, generally upslope) usually have high flame lengths and significant potential for crown injury and tree mortality. **Backing fires** (opposite the direction of the main active fire, generally downslope) typically spread more slowly than head fires, result in more complete combustion of fuel, and cause less damage to trees unless ground fuel burns hot enough to kill tree roots and the lower cambium. **Flanking fires** (tangential to the direction of the main active fire, generally across slope) are intermediate in spread rate and effects. All of these fire characteristics are modified by weather conditions, discussed in a subsequent section.

Fuel Treatments: Thinning and Prescribed Fire

Where and when should fuel treatments be conducted? Although this is partially a policy question, it is also relevant to the science and management of fuel and fire. Schmidt et al. (2002) provided a classification that suggests where fuel treatments might be prioritized (especially Condition Class 3) at a coarse spatial scale **if** the objective is to return fuel to historical conditions and reduce fire hazard. This is a restoration and fire management objective for many low-elevation dry forests in the Western United States. This objective is more difficult to justify for high-elevation, cold, and wet forests.

A collateral objective of fuel treatment is often to create conditions that are defensible by fire suppression if wildfire should occur. This is typically in areas that do not have steep slopes and are accessible by firefighting equipment and personnel. Accessibility often limits the possibility of fuel treatment in wilderness and other unroaded areas. Areas with steep slopes are also difficult to treat in terms of the logistics of removing downed logs and fuel by thinning, as well as the safety of using prescribed fire. The presence of threatened and endangered species may also preclude fuel treatments. As noted later in this document, conducting isolated or random fuel treatments without considering the fuel and fire hazard across the broader landscape may be ineffective.

Fuel treatments typically target crown, ladder, and surface fuels with silvicultural operations and prescribed burning to modify vegetation in each stratum (Peterson et al. 2003). **Canopy and ladder fuels** are modified by forest thinning operations that target crown classes, stand basal area, and canopy bulk density. **Surface fuel**, particularly woody fuel and litter, can be modified by prescribed fire and a variety of treatments that remove and reduce fuel (e.g., pile-and-burn, and crushing and chopping [mastication]). Silvicultural treatments and prescribed fire can also modify vegetation dynamics in the short and long terms. Opening forest canopies increases light to the forest floor, with the potential for increased grass and shrub fuel, altering fuel structure and in some cases successional pathways for vegetation.

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, Peterson et al. 2003). Management of thinning residues affects the post-thinning combustion environment, with an almost certain increase in fine fuel 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 fuel. Equipment that removes large stems from the stand prior to further processing typically increases the fuel load less than felling and processing within the stand. Helicopter yarding and cable-based systems increase surface fuel unless treated, because logs are removed but slash from tree crowns is left behind.

Lop-and-scatter, cutting residual fuel into pieces and scattering them on the forest floor, has often been used for the unmerchantable portion of thinning. Unless this material is broken and compressed into the ground fuel, it can increase fireline intensity and flame length. Prescribed burning of material left on site can effectively reduce residual surface fuel in some situations. Pile-and-burn generally is more effective at removing thinning material from the forest floor, particularly from the base of living trees. If burning is deemed unacceptable because of smoke production or carbon release, the material can be removed from the forest or chipped and left on site. A collateral negative impact of ground-based thinning is that roads and skid trails can cause soil compaction and damage low vegetation.

Silvicultural thinning is implemented with the principal objective of reducing fuel loads and ultimately modifying fire behavior. However, breakage, handling of slash, and disruption of the forest floor can increase fine-fuel loading (Agee 1996, Fitzgerald 2002, Weatherspoon 1996).

Rate of spread and fireline intensity in thinned stands are usually significantly reduced only if thinning is accompanied by reducing and altering the arrangement of surface fuel created by the thinning operation (Graham et al. 1999, 2004). Prescribed burning is often used to reduce surface fuel. 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 ladder fuel must be minimal, a condition that may exist only after thinning. Retention of larger, more fire-resistant trees in silvicultural prescriptions reduces fire damage to the overstory even if damage is high to smaller, residual (and less fire-resistant) trees in a subsequent fire (Weatherspoon and Skinner 1995). In some cases, removal of trees from the canopy and understory could conceivably increase surface wind movement (Albini and Baughman 1979) and facilitate drying of live and dead fuel (Pollet and Omi 2002), although effective removal of ladder and surface fuel should mitigate these factors by reducing the fuel load and potential for fire spread.

Thinning and prescribed fire target different components of the fuelbed of a given forest stand or landscape (Peterson et al. 2003). 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 fuel, creating gaps, and in some cases reducing ground fuel.

Prescribed burning affects potential fire behavior by reducing fuel continuity on the forest floor, thereby slowing fire spread rate, reducing fire intensity, and reducing the likelihood of fire spreading into ladder fuel and the crown. Prescribed fire is typically cheaper per unit area than thinning and in some cases can be used to reduce stem density and ladder fuel by killing (mostly) smaller trees. This has proven to be effective as the sole means of fuel treatment in the mixed-conifer forest of the southern Sierra Nevada, California (Kilgore and Sando 1975, McCandliss 2002, Stephenson et al. 1991), and may be effective in other Western forests if carefully applied, particularly in stands with large, fire-resistant trees. However, potential secondary effects pose management challenges. Prescribed fires may kill individual trees and clumps of trees that are not targeted for removal. Fallen dead branches increase fine fuel that helps propagate surface fire, and fallen boles add to the potential for energy release and smoke production. Prescribed fires create smoke that decreases air quality in local communities and cause charring that affects esthetic qualities of the residual stand and landscape.

The type and sequence of fuel treatments depend on the amount of surface fuel present; the density of understory and midcanopy trees (Fitzgerald 2002); long-term potential effects of fuel treatments on vegetation, soil, 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 fuel, thereby providing maximum protection from severe fires in the future. Given current accumulations of fuel 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., mastication), to reduce crown-fire hazard.

Evidence for Fuel Treatment Effectiveness

The majority of the scientific literature supports the effectiveness of fuel treatments in reducing the probability of crown fire (e.g., Agee 1996; Edminster and Olsen 1996; Helms 1979; Kilgore and Sando 1975; Martinson and Omi 2002; Omi and Martinson 2002; Pollet and Omi 2002; Scott 1998a, 1998b; van Wagtendonk 1996; Wagle and Eakle 1979; Weatherspoon and Skinner 1995). Fuel loading may determine fire severity in historically low and moderate fire-severity regimes, but because the relative influence of fuel and weather differs between forest ecosystems (Agee 1997), it is difficult to develop precise quantitative guidelines for fuel treatments. A majority of the evidence supporting the effectiveness of fuel treatments for reducing crown-fire hazard is based on informal observations (Brown 2002, Carey and Schumann 2003), postfire inference (Omi and Kalabokidis 1991, Pollet and Omi 2002), and simulation modeling (Finney 2001, Stephens 1998).

Observations from the Hayman Fire in Colorado (Graham 2002) suggest that prescribed fire treatments effectively reduced fire behavior on relatively gentle slopes, with crown fires diminishing to surface fires in stands with lower stem densities and surface fuel on days when weather conditions were less extreme. The results of fuel treatments were less clear at locations that burned when fire weather was extreme. Observations from the Cone Fire in California in 2002 (Agee and Skinner, in press) also suggest that past thinning treatments can reduce crown fires to surface fires.

Empirical studies comparing on-the-ground effects of fire in treated versus untreated stands **under extreme fire weather conditions** and **on steep slopes** are rare (Pollet and Omi 2002). In response to the lack of knowledge in this area, the Fire and Fire Surrogates study (http://www.fs.fed.us/ffs) was developed through the Joint Fire Science Program to quantify the consequences and trade-offs of alternative fire and thinning treatments. Although the small number of treatments (control, thinning, fire, thinning plus fire) are not comprehensive of the diverse forest landscapes now being considered for fuel treatments, the study will provide valuable new empirical data that can inform future fuel treatment decisions.

The Role of Fire Weather

Fire weather is often perceived at different scales. **Weather at small spatial and temporal scales** regulates fuel moisture content, which influences diurnal and day-to-day variation in flammability. Temperature, relative humidity, and wind are monitored by fire managers throughout the fire season to determine fire danger and the potential for flammability and fire spread during wildfires and prescribed fires. **Weather at broad spatial and temporal scales**, or **climatology**, often controls extreme fire behavior (e.g., crown-fire spread) and the occurrence of large fires (e.g., Flannigan et al. 2000), although this generalization varies considerably among biogeographic regions (Gedalof et al., in press). The relative influence of fuel and climatology has been poorly quantified for most forest ecosystems and regions of the United States.

Extensive scientific data exist on key aspects of fuel, topography, and weather that influence fire behavior and severity, especially for surface fire. However, owing to the logistical constraints of working in wildfires, applicability of empirical data and current theory is more limited for extreme fire weather conditions (Agee 1997). For example, a comparison of BEHAVE (Andrews 1986) and the Fire Behavior Prediction (FBP) model (Forestry Canada Fire Danger Group 1992) in Canadian mixed-wood boreal forest showed that FBP was more sensitive to variation in weather, and BEHAVE was more sensitive to variation in vegetation (Hely et al. 2001). This disparity in how fire behavior is modeled in the two common systems used in North America indicates a disparity in the basis for describing the interaction of fuel and weather–empirical for FBP, laboratory based for BEHAVE.

Large fires tend to occur most often during and following periods of dry weather that lower fuel moisture (e.g., Agee 1997, Heyerdahl et al. 2001). Dry weather and the potential for ignitions are more common during distinct climatic modes, such as high-pressure blocking ridges (Gedalof et al., in press). In addition, temporal variation in large fires in the West is at least partially controlled by variation in long-term climatic patterns. The occurrence of large fires in ponderosa pine forests of the Southwest (Allen et al. 2002, Swetnam and Betancourt 1990) and ponderosa pine-Douglas-fir forests of the southern Rocky Mountains (Veblen et al. 2000) is related to 3- to 7-year phases of the El Niño Southern Oscillation (ENSO), whereas large fires in ponderosa pine-Douglas-fir forests of the inland Pacific Northwest are related to 20- to 40-year phases of the Pacific Decadal Oscillation (PDO) (Gedalof et al., in press; Hessl et al. 2004). Extreme fire weather is more common during warm phases of the ENSO and PDO, and along with steep slopes, creates the conditions that facilitate rapid spread of crown fire and long-distance transport of burning embers (spotting).

Integrating Tools to Provide Quantitative Fuel-Treatment Guidelines

Management of fuel across large landscapes is required to effectively reduce the area and severity of fires, as well as effects on local communities. In addition, because a small proportion of fires (approximately 1 percent) is responsible for as much as 98 percent 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.

Silvicultural Thinning

Silvicultural options for fuel treatment are summarized in Graham et al. (1999) and Fitzgerald (2002), which provide visual displays of thinning treatments and explain how treatments address fuel loading. Thinning, the removal of specific components of the tree stratum, is used to modify fire hazard, improve growth and vigor of residual trees, and promote certain types of wildlife habitat. Several thinning methods exist (Graham et al. 1999): (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 forest canopy components are compared in table 1, and visualizations of an unthinned stand (fig. 5) are compared to three thinning treatments (figs. 6–8).

Table 1—Effects of thinning treatments on key components of canopy structure related to crown-fire hazard

Thinning treatment	Canopy base height	Canopy bulk density	Canopy continuity	Overall effectiveness
Crown	Minimal	Lower in upper canopy but minimal effect in lower canopy	Lower continuity in upper canopy but minimal effect in lower canopy	May reduce crown-fire spread slightly but torching unaffected
Low	Large increase	Large effect in lower canopy, some effect in upper canopy depending on tree sizes removed	Large effect in lower canopy, some effect in upper canopy depending on tree sizes removed	Will greatly reduce crown-fire initiation and torching
Selection	None	Lower in upper canopy but minimal effect in lower canopy	Lower continuity in upper canopy but minimal effect in lower canopy	May reduce crown-fire spread slightly if many trees removed but 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

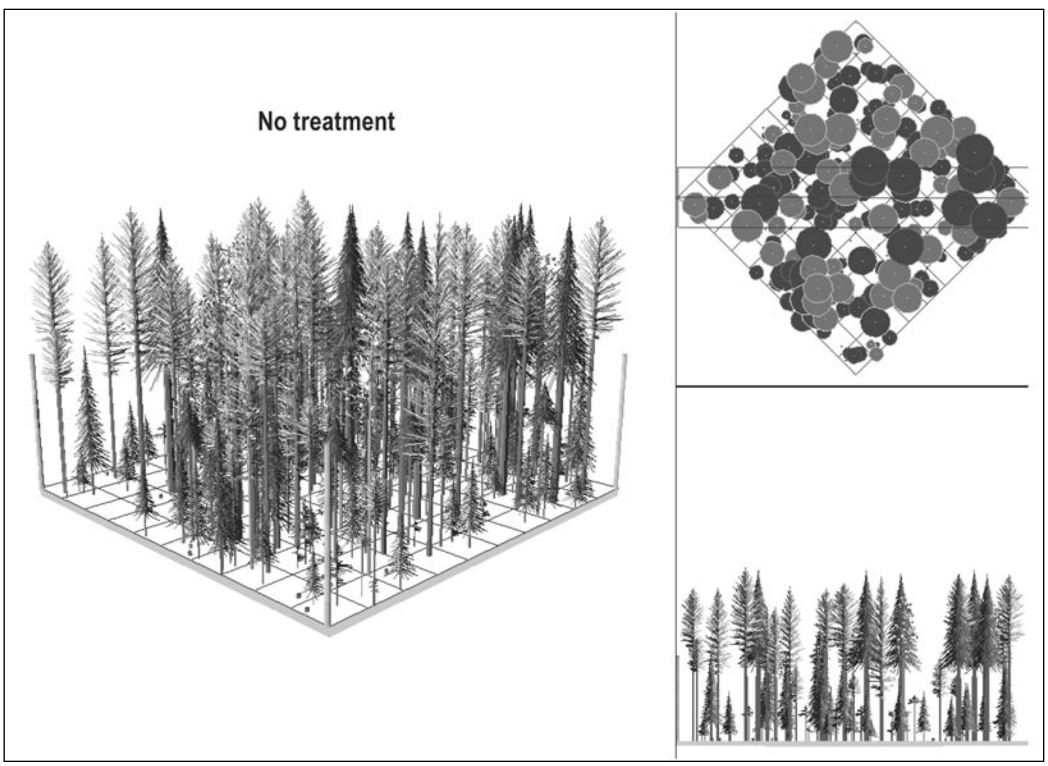

*Figure 5—A mixed-conifer stand from Pack Forest, Eatonville, Washington. Initial stand condition is 278 trees per acre, basal area 376 $ft^2 \cdot ac^{-1}$, average diameter 12 in, comprising Douglas-fir, western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), red alder (*Alnus rubra*), and black cottonwood (*Populus trichocarpa*). Visualizations in figures 5 through 8 are derived with the Forest Vegetation Simulator.*

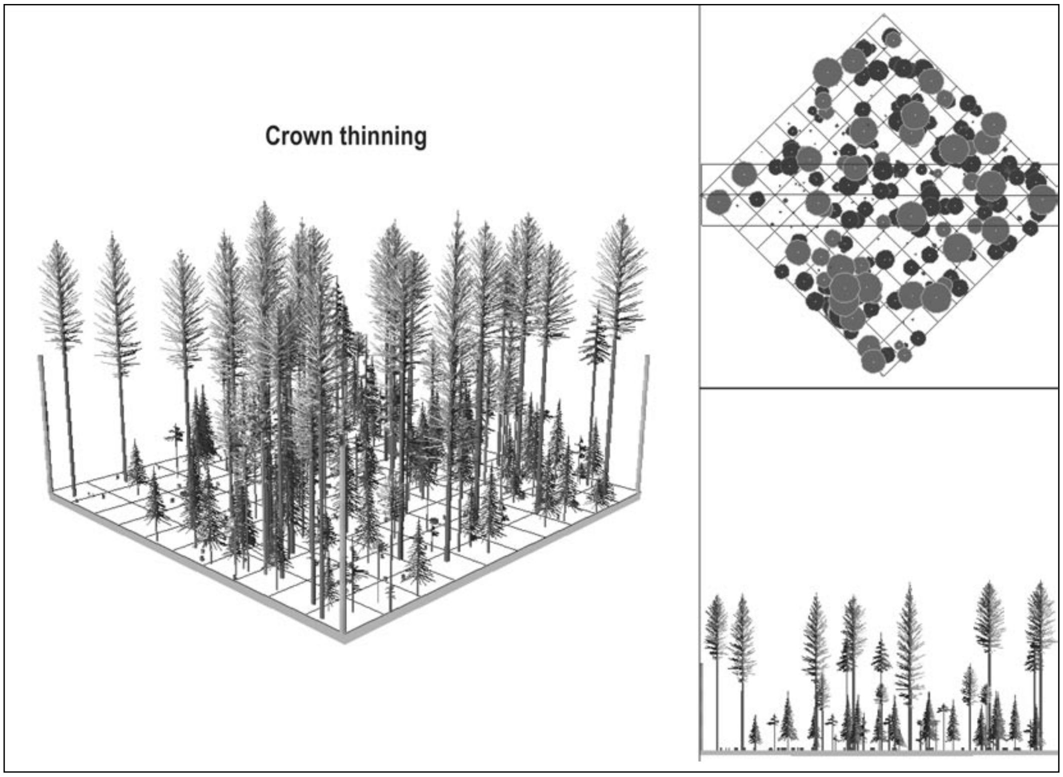

Figure 6—The mixed-conifer stand from figure 5, showing the results of crown thinning.

Crown thinning (thinning from above) (fig. 6) removes trees with larger diameters but favors the development of the most vigorous trees of these same size classes. 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 rather than eliminating all suppressed trees.

Low thinning (thinning from below) (fig. 7) primarily removes trees with smaller diameters. This method mimics mortality caused by intraspecific and interspecific competition or abiotic factors such as wildfires. Thinning from below primarily targets intermediate and suppressed trees, although codominant and dominant trees are not exempt from harvest. If codominant and dominant trees are removed, all smaller, intermediate, and overtopped trees are also removed (Smith et al. 1997). Often, diameter limits are used to establish cutting targets. For example, a thinning prescription may call for all trees of less than 9 in diameter to be removed.

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. This thinning method has limited applicability in forest management programs with multiple objectives (e.g., structural diversity, wildlife habitat) because it limits future stand options.

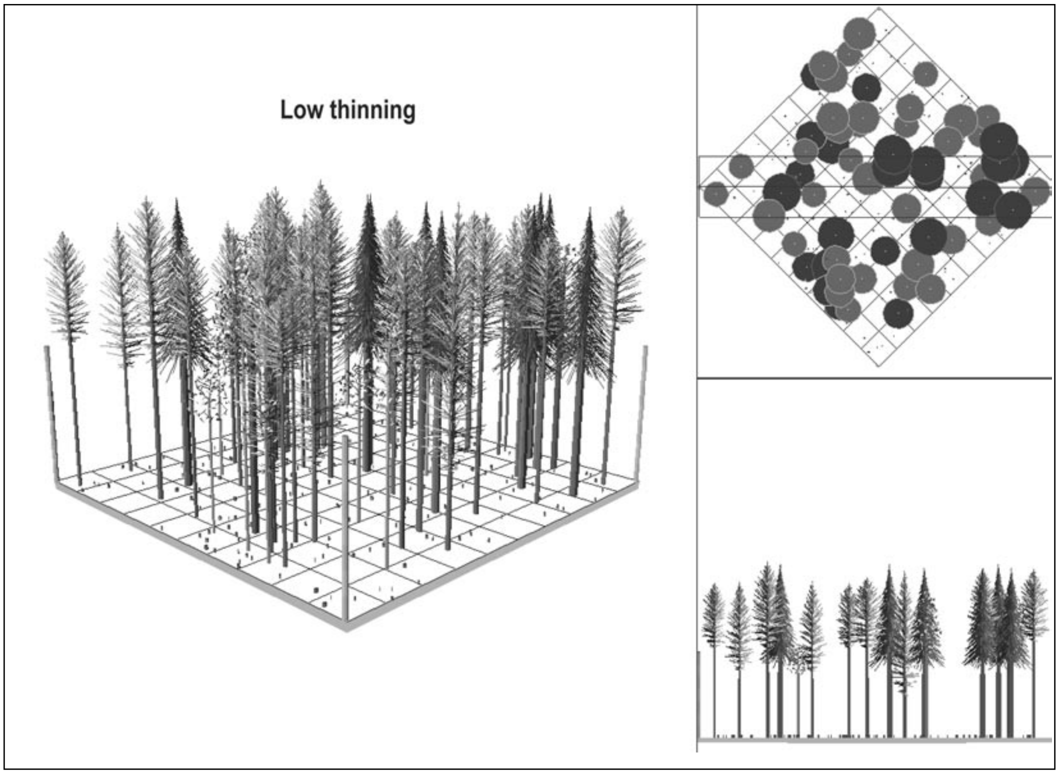

Figure 7—The mixed-conifer stand from figure 5, showing the results of low thinning; all stems of less than 9 in diameter were removed.

Free thinning (fig. 8) primarily favors selected individual trees in a stand while the rest of the stand remains untreated. Cuttings are designed to release residual trees from competition 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., 6- by 6-ft spacing) or other geometric pattern, with little regard for their position in the crown canopy. This type of thinning is often applied in young plantations with high density, and employed only in the first thinning of a stand. Space thinning and row thinning can be used to accomplish geometric thinning.

Variable-density thinning combines thinning from below and one or more of the other silvicultural thinning 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 at small and large spatial scales

Graham et al. (1999) provided examples of how specific thinning treatments affecting stand density, canopy base height, and canopy bulk density can be linked with fire behavior fuel

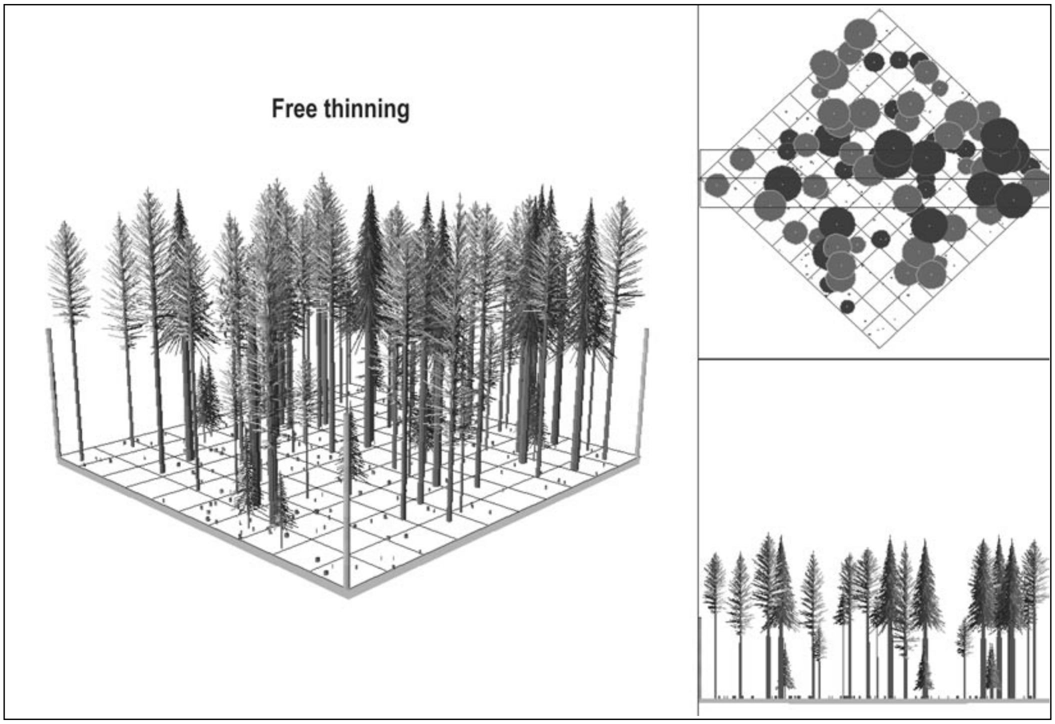

Figure 8—The mixed-conifer stand from figure 5, showing the results of free thinning.

models (Anderson 1982), which are standardized representations of surface fuel sizes and mass. This approach determines if surface fire will propagate to crown fire, thus providing a rough estimate of the likelihood of crown fire following fuel treatments.

Scott and Reinhardt (2001) provided 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 2003) incorporates much of this analytical capability. It allows users to enter current stand and surface fuel conditions; simulate thinning treatments, surface-fuel treatments, and fire; and examine the effects of these treatments on surface fuel, canopy fuel, 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 (e.g., Fiedler and Keegan 2002).

Quantifying Fire Hazard and Fire Potential

Accurate quantification of fuel in the canopy and shrub/small tree strata is necessary to understand the combustion environment of crown fire (Cruz et al. 2003, Scott and Reinhardt 2001). Potentially effective techniques for reducing crown-fire occurrence and severity are to (1) increase canopy base height, (2) reduce canopy bulk density (Agee 1996, Scott and Reinhardt 2001), (3) reduce forest canopy continuity (Cruz et al. 2002, Scott and Reinhardt 2001, van Wagner 1977), and (4) reduce surface fuel (Graham et al. 2004).

With the caveat that few empirical data are available that quantify the effects of specific fuel treatments on fire behavior, objective and quantifiable fuel-treatment criteria will assist fire managers and silviculturists in achieving desired conditions for fuel to reduce fire hazard. Desired conditions for canopy base height, crown bulk density, and continuity depend on management objectives for fuelbeds and crown-fire hazard. For example, fire managers often make assessments of potential fire behavior for specific fire weather, such as the 50^{th}-, 90^{th}-, and 97^{th}-percentile weather severity, or for moistures of 1-, 10-, and 100-hr timelag fuels (equivalent to fuel size classes of <0.25 in, 0.25 to 1.0 in, and 1.0 to 3.0 in, respectively). In addition, desired conditions must be adjusted for slope, because even greater fuel reductions are needed on steep slopes owing to convective winds and heating and intensification of fire behavior 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 potential crown-fire initiation (Scott 2002, Scott and Reinhardt 2001) (fig. 9). For many dry forests, this value may be 20 feet or more (Jain et al. 2001). Using the flame length for the worst case fire weather (e.g., 97^{th}-percentile weather severity) as a standard would be the least risky option. The required reduction in stem density and basal area will differ 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 2004).

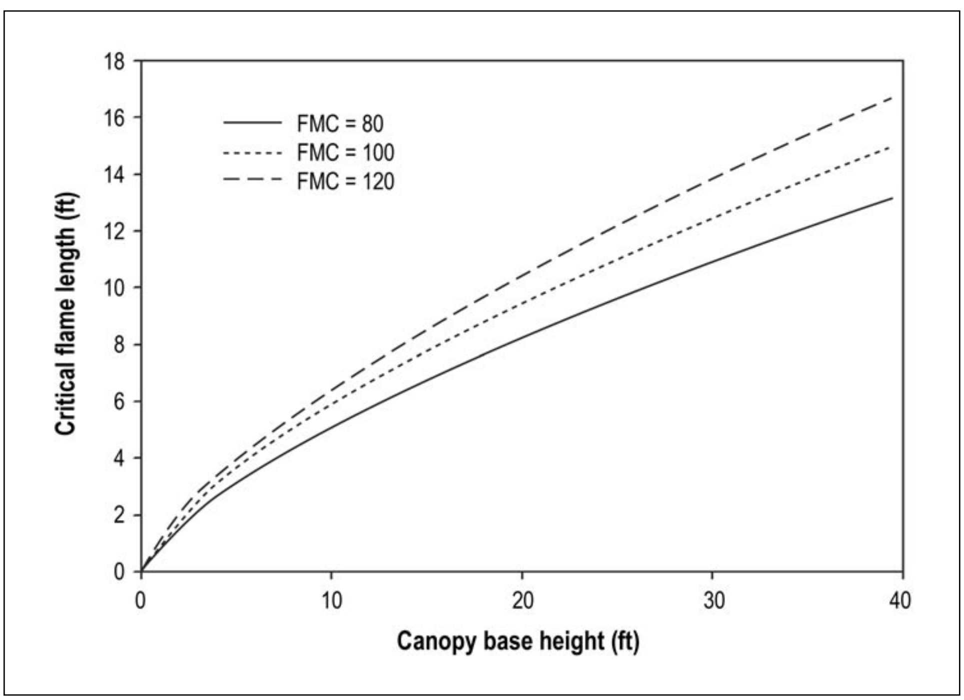

Figure 9—Critical flame length is less than canopy base height when canopy base height is greater than about 3 ft. The lines represent foliage moisture content (FMC) of 80 percent, 100 percent, and 120 percent. (From Scott and Reinhardt 2001)

Canopy bulk density should be maintained below a critical threshold (a function of fire weather and fire rate of spread) such that a crown fire can make a transition back to a surface fire. This threshold is not well defined, although canopy bulk density <0.10 kg·m^{-3} (= 0.0062 lb·ft^{-3}, canopy bulk density by convention is always expressed in metric units) seemed to be sufficient in the 1994 Wenatchee Fire in <100-year-old ponderosa pine-Douglas-fir stands on the east side of the Cascade Range of Washington (Agee 1996). The required reduction in stem density and basal area will differ considerably between stands, depending on initial stem density and canopy structure (fig. 10). 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 percent 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 2004).

Basic fire behavior principles and forest allometric relationships can be used to establish critical levels of canopy bulk density below which crown-fire initiation and spread are unlikely. These levels, in combination with information on fire weather, surface fuel data, and stand data, can be used to define a stand that is unlikely to generate or allow the spread of crown fire (Agee 1996). Crown bulk densities were calculated for ponderosa pine, Douglas-fir, and grand fir, associated with various combinations of mean stem diameter and stem density (Agee 1996) (table 2).

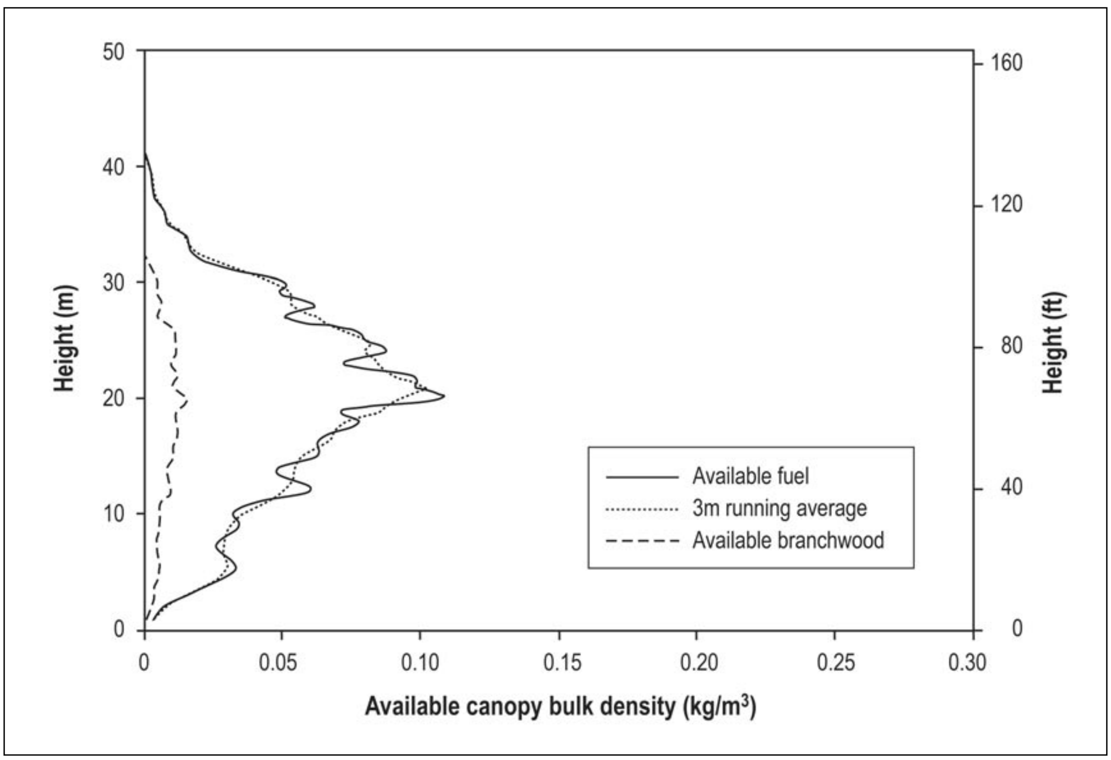

Figure 10—Vertical profile of canopy bulk density in a Sierra Nevada mixed conifer stand. Effective canopy bulk density is considered to be the maximum 3-m running mean (0.21 kg • m^{-3} in this stand). Canopy bulk density varies greatly depending on species, stand age, and stem density. The vertical distribution shown in this example is typical of dense, multistoried stands. Note that canopy bulk density by convention is always expressed in metric units.

Table 2—Canopy bulk density by diameter class and density for ponderosa pine (PP), Douglas-fir (DF), and grand fir (GF)

Mean diameter	Species	Stem density (trees per acre) 120	250	500	1,000	2,000
Inches		*Kilograms per cubic meter*				
0.5	PP	0.001	0.002	0.003	0.009	0.018
	DF	.002	.003	.005	.011	.022
	GF	.002	.003	.007	.014	.027
3.0	PP	.003	.007	.014	.028	.055
	DF	.004	.007	.014	.028	.056
	GF	.006	.012	.024	.047	.094
8.0	PP	.005	.010	.021	.041	.083
	DF	.009	.017	.034	.068	.136
	GF	.008	.016	.033	.066	.132
12.0	PP	.010	.020	.041	.082	.164
	DF	.012	.025	.049	.099	.198
	GF	.013	.026	.052	.103	.103
18.0	PP	.011	.023	.047	.248	.361
	DF	.019	.039	.078	.191	.252
	GF	.023	.047	.095	.247	.247

Source: Agee 1996.

Canopy bulk densities are generally lowest for ponderosa pine and highest for grand fir. Differences between species are typically not as great as differences between densities and size classes. However, fire tolerance is another matter, and thin-barked species such as grand fir are sensitive to surface fire, whereas thick-barked species such as ponderosa pine are not. Therefore, canopy bulk density is just one factor to consider in thinning prescriptions; the appropriate threshold is subjective and depends on fire weather conditions and rate of fire spread. Because table 2 represents idealized single-species stands with uniform diameter, uniform density, and a single canopy stratum, caution should be used in applying these values; empirical data for actual stands should be used if available.

Canopy continuity is more difficult to quantify and is a more 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 can spread through horizontal and vertical heat flux and spotting from embers, so relatively wide spacing of canopies is necessary to effectively reduce crown-fire hazard. An example of a field-based rule is that the distance between adjacent tree crowns should be the average diameter of the crown of codominant trees in the stand.

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 fuel. For example, Jain et al. (2001) suggested that stands with a crown competition factor <140 have canopy densities low enough to greatly reduce probability of crown fire. Additional empirical data are needed to determine how well this parameter works as a guideline for thinning.

An alternative approach, the Fuel Characteristic Classification System (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). A given set of fuel data can be associated with approximately 120 combinations of surface-fire potential, extreme-fire potential, and fire-effects potential. A three-digit code is used to represent (1) **surface-fire potential** (reaction potential, spread potential, and flame-length potential), (2) **extreme-fire potential** for canopy and shrub fuel (torching potential, dependent crown-fire potential, independent crown-fire potential), and (3) **fire-effects potential** (for flame available, smoldering available, and residual available fuel). The FCCS contains empirical fuelbed data from throughout the United States compatible with forest stand inventory data used by silviculturists. These fuelbeds can be linked with specific fuel treatments at any spatial resolution. The FCCS will be available online in 2005.

Assessing Large-Scale Fuel Conditions

Effective fuel treatment programs must consider the spatial pattern of fuel 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 fuel, multiple fires, and spotting, so a "firesafe" landscape needs to encompass hundreds to thousands of acres with desired fuel conditions strategically located in any particular management unit (Finney 2003). Treating small or isolated stands without assessing the broader landscape may be ineffective in reducing large-scale crown fire.

The efficacy of fuel treatments across large landscapes can be visualized by using spatially explicit data on fuel and fire hazard generated by 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). The 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, USDA FS 2004) and ORGANON (Hann et al. 1997, OSU 2004) are embedded within the system.

Silvicultural treatments can be implemented in LMS at designated times during a planning cycle (e.g., 50-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 system also has the ability to add new records (regeneration or ingrowth files). The effects of treatments can be readily analyzed with graphs, tables, and stand and landscape visualizations for any period during the planning cycle.

The LMS or another analysis tool can be used to display spatial patterns of forest structures and fuel across a landscape for existing conditions compared to patterns produced by various fuel-treatment scenarios (fig. 11). Fuel conditions can be quantified with the FCCS, fuel models, or other

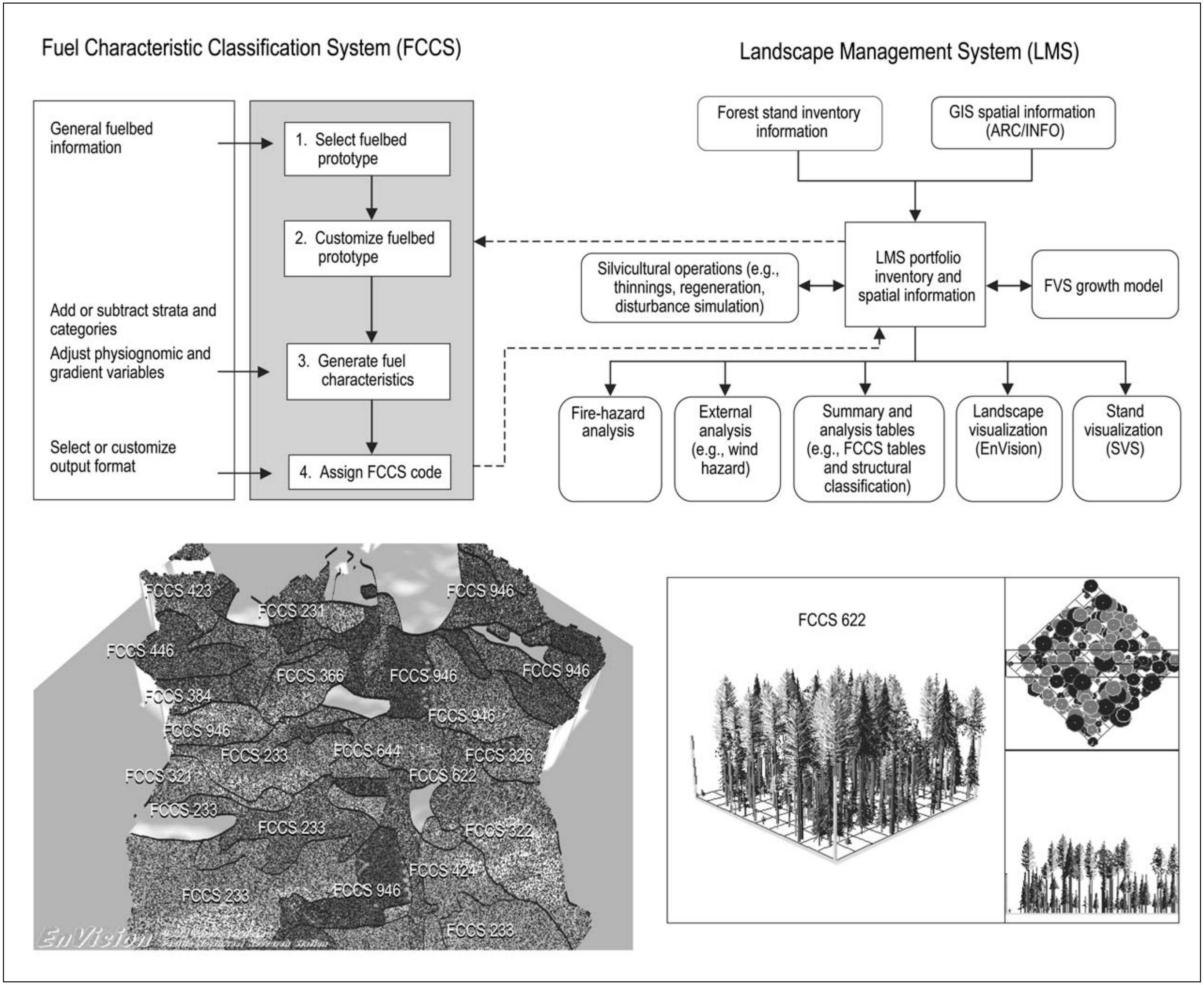

Figure 11—Example of how a landscape analysis system can be combined with fuel classification to assess spatial fuel patterns.

fire-hazard parameters. 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 may be the most effective approach for managing fuel and reducing crown-fire hazard at large spatial scales.

Simulation modeling can also be used to predict propagation of fire at broad spatial scales. The primary tool used to model fire spread, including crown fire, for forest landscapes is FARSITE (Finney 1998). This program integrates geospatial fuel 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 fuel data and good weather 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 Fire and Fuels extension of FVS (Reinhardt and Crookston 2003) 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 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 (say, every 5 to 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 differ by species, elevation, aspect, climatic zone, and soil fertility. Broad spatial perspectives and tools are the key to planning and implementing management for a fire-resilient landscape.

Using Scientific Principles for Adaptive Fuel Management

Forest ecosystems are inherently complex, and the effectiveness of site-specific modification of fire hazard is directly proportional to the quantity and quality of local data on forest structure and fuel. Fire behavior modeling is reasonable for surface fires and small spatial scales, but is in its infancy for crown fires and large spatial scales, and our understanding of the interaction of fuel, topography, and weather is better for small scales and moderate fire weather than for large scales and severe fire weather. In the face of this complexity, it is important to focus on basic scientific principles that will aid decisionmaking and guide future data collection (table 3).

These basic principles of fire resilience can be applied quantitatively as well as qualitatively if adequate data are available. The relative importance of each principle may vary depending on management objectives and the specific location of fuel treatments (e.g., forests adjacent to structures and local communities versus forests in 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.

The relationship between fuel treatments and wildfires is based on documented scientific

Table 3—Principles for fire-resilient forests

Principle	Effect	Advantage	Concerns
Reduce surface fuel	Reduces potential flame length	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 tree-to-tree crown fire less probable	Reduces crown-fire potential	Surface wind may increase, surface fuel may be drier
Retain larger trees	Thicker bark and taller crowns	Increases survivability of trees	Removing smaller trees is economically less profitable

Source: Agee 2002b.

principles but a limited empirical database. Appropriate types of thinning and subsequent residue treatment are clearly useful in reducing surface- and crown-fire hazards under a wide range of structural, fuel, and topographic conditions. Steep slopes and extreme fire weather will always be a challenge for fire management and require higher relative removal of fuel to reduce fire hazard. Resource managers need to use the best information available and expert opinion on local conditions, as well as clearly state the level of acceptable risk relative to treatments for any particular forest stand or landscape. The growing empirical database on how forest structure affects large wildfires will inform adaptive fuel management and provide new quantitative insights in the years ahead.

Adherence to four basic but challenging points will increase the effectiveness of adaptive fuel management. First, we need high-quality empirical data on fuel and geographic information system tracking of changes in fuel over time. Second, fire managers, silviculturists, and other resource specialists need to work together to develop prescriptions that effectively reduce fire hazard and achieve other resource objectives. Third, local management units need to monitor posttreatment fuel conditions and the effectiveness of fuel treatments when wildfire occurs. Finally, a rigorous schedule of periodic fuel treatments should be implemented to maintain the desired level of fire hazard and other conditions.

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Metric Equivalents

When you know:	Multiply by:	To find:
Feet (ft)	0.3048	Meters (m)
Acres (ac)	.405	Hectares (ha)
Pounds per acre ($lb \cdot ac^{-1}$)	1.12	Kilograms per hectare ($kg \cdot ha^{-1}$)
Pounds per cubic foot ($lb \cdot ft^{-3}$)	16.2	Kilograms per cubic meter ($kg \cdot m^{-3}$)

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