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Science Basis for Changing Forest Structure to Modify Wildfire Behavior and Severity

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Technical Editors:

Dr. Russell T. Graham, Rocky Mountain Research Station
Dr. Sarah McCaffrey, North Central Research Station
Dr. Theresa B. Jain, Rocky Mountain Research Station

Abstract

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Fire, other disturbances, physical setting, weather, and climate shape the structure and function of forests throughout the Western United States. More than 80 years of fire research have shown that physical setting, fuels, and weather combine to determine wildfire intensity (the rate at which it consumes fuel) and severity (the effect fire has on vegetation, soils, buildings, watersheds, and so forth). Millions of acres of forestlands (mainly in dry forests dominated by ponderosa pine and/or Douglas-fir) contain a high accumulation of flammable fuels compared to conditions prior to the 20th century. Forests with high stem density and fuel loading combined with extreme fire weather conditions have led to severe and large wildfires (such as those seen in the summers of 2000, 2002, and 2003) that have put a number of important values at risk. Although homes in the path of a wildfire are perhaps the most immediately recognized value, these wildfires also put numerous other human and ecological values at risk, such as power grids, drinking water supplies, firefighter safety, critical habitat, soil productivity, and air quality.

For a given set of weather conditions, fire behavior is strongly influenced by stand and fuel structure. Crown fires in the dry forest types represent an increasing challenge for fire management as well as a general threat to the ecology of these forests and the closely associated human values. Crown fires are dependent on the sequence of available fuels starting from the ground surface to the canopy. Limiting crown fire in these forests can be accomplished by actions that manage in concert the surface, ladder, and crown fuels. Reducing crown fire and wildland fire growth across landscapes decreases the chances of developing large wildfires that affect human values adjacent to forested areas. However, a narrow focus on minimizing crown fire potential will not necessarily reduce the damage to homes and ecosystems when fires do occur. Homes are often ignited by embers flying far from the fire front, and by surface fires. Fire effects on ecosystems can also occur during surface fires where surface and understory fuels and deep organic layers are sufficient to generate high temperatures for long periods.

Fuel treatments can help produce forest structures and fuel characteristics that then reduce the likelihood that wildfires will cause large, rapid changes in biophysical conditions. Fuel treatments can also help modify fire behavior sufficiently so that some wildfires can be suppressed more easily. Subsequent, sustained fuel treatments can maintain these conditions. Different fuel reduction methods target different components of the fuel bed. Thinning mainly affects standing vegetation, and other types of fuel treatments such as prescribed fire and pile burning woody fuels are needed to modify the combustion environment of surface fuels. In forests that have not experienced fire for many decades, multiple fuel treatments—that is, thinning and surface fuel reduction—may be required to significantly affect crown fire and surface fire hazard. Fuel treatments cannot guarantee benign fire behavior but can reduce the probability that extreme fire behavior will occur. Fuel treatments can be designed to restore forest conditions to a more resilient and resistant condition than now exists in many forests, and subsequent management could maintain these conditions, particularly in dry forests (ponderosa pine and Douglas-fir) where crown fires were historically infrequent. The degree of risk reduction will depend to some degree on the level of investment, social and economic acceptability of treatments, and concurrent consideration of other resource values (for example, wildlife).

This report describes the kinds, quality, amount, and gaps of scientific knowledge for making informed decisions on fuel treatments used to modify wildfire behavior and effects in dry forests of the interior Western United States (especially forests dominated by ponderosa pine and Douglas-fir). A review of scientific principles and applications relevant to fuel treatment primarily for the dry forests is provided for the following topics: fuels, fire hazard, fire behavior, fire effects, forest structure, treatment effects and longevity, landscape fuel patterns, and scientific tools useful for management and planning.

Key words: Thinning, fuel treatments, prescribed fire, dry forests

Cover: Intense crown fire behavior exhibited by the Star Gulch Fire burning on the Boise National Forest in Idaho in 1994 (K. Watenmaker photo).

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Technical Editors:

Dr. Russell T. Graham, Rocky Mountain Research Station
Dr. Sarah McCaffrey, North Central Research Station
Dr. Theresa B. Jain, Rocky Mountain Research Station

Contributing Authors:

Dr. David Peterson, Pacific Northwest Research Station (PNW)
Dr. Mark Finney, Rocky Mountain Research Station (RMRS)
Dr. Carl Skinner, Pacific Southwest Research Station (PSW)
Dr. Merrill Kaufmann, RMRS
Morris Johnson, PNW
Dr. Wayne Shepperd, RMRS
Michael Harrington, RMRS
Dr. Robert Keane, RMRS
Dr. Donald McKenzie, PNW
Dr. Elizabeth Reinhardt, RMRS
Dr. Kevin Ryan, RMRS

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Dr. Tom Zimmerman, USDA Forest Service, Southwestern Region
Dr. Dave Cleaves, USDA Forest Service, Washington Office
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Paula Seamon, The Nature Conservancy
Dr. Thomas Swetnam, University of Arizona
Dr. Thomas Waldrop, USDA Forest Service, Southern Research Station
Andy Youngblood, USDA Forest Service, Pacific Northwest Experiment Station
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Contents

Key Points

Science Basis for Changing Forest Structure to Modify Wildfire Behavior and Severity

General Technical Report RMRS-GTR-120

More than 80 years of fire research have shown that physical setting, weather, and fuels, combine to determine wildfire intensity and severity. Of these three factors, fuels (vegetation) is the only one that can be treated. The effectiveness and effects of various fuel treatments for restoring dry forests in the Western United States are summarized in this paper. A considerable amount of information is available on fire behavior and the impacts forest structure and fuel modifications have on fire intensity and severity. Some key findings of this paper include:

Treated fuels on the Boise Basin Experimental Forest, Idaho. (K. Watenmaker photo)

- Historically, many dry forests in the Western United States, such as those dominated by ponderosa pine and Douglas-fir were frequently (4 to 25 years) burned by low intensity surface fires.
- Changes in forest structure and composition over the past 60 to 100 years have increased fuel loads and made many of the ponderosa pine forests more susceptible to highly intense and highly severe fires.
- Models, field observations, and experiments indicate that for a given set of weather conditions, fire behavior is strongly influenced by fuel structure and composition.
- Crown fires are dependent on the sequence of available fuels starting from the ground surface to the canopy. Crown fires are more likely to occur when sufficient surface fuels are available to ignite ladder fuels and/or the lower crowns of overstory trees.
- Reducing the likelihood of crown fires requires decreasing the amount, density, and continuity of surface fuels, and removing ladder fuels.
- Surface and ground fires especially those with long (hours to days) residence times can destroy soil organic matter, reduce forest productivity, and on some settings fuse soil particles that in turn can dramatically increase soil erosion compared to unburned sites.
- In forests that have not experienced fire for many decades, multiple fuel treatments—that is, thinning and surface fuel reduction—may be required to significantly affect crown fire and surface fire hazard.
- Models and observations of landscape scale fire behavior and the impacts of fuel treatments clearly suggest that a landscape approach is more likely to have significant overall impacts on fire spread, intensity, perimeters, and suppression capability than an approach that treats individual stands in isolation.

Untreated fuels on the Boise Basin Experimental Forest, Idaho. (K. Watenmaker photo)

Science Basis for Changing Forest Structure to Modify Wildfire Behavior and Severity

Introduction

Fire, other disturbances, physical setting, weather, and climate shape the structure and function of forests throughout the Western United States (Daubenmire and Daubenmire 1968, Perry 1994, Hann and others 1997, Agee 1998b, Schmoldt and others 1999). More than 80 years of fire research shows that fuels (that is, composition, amount, structure, moisture content of dead and live vegetation and detritus), physical setting (slope, aspect, elevation, relief, soils, and so forth), weather (short- and long-term wind, humidity, precipitation, and so forth), and climate combine to determine wildfire intensity (the rate at which a fire is producing thermal energy in the fuel-climate environment, most often measured in terms of temperature and heat yield) and severity (the effect the fire has on vegetation, soils, buildings, watersheds, and so forth; most often expressed in terms of the postwildfire condition of litter, soil, trees, and so forth) (Larsen 1921, Gisborne 1923, Wells and Campbell 1979, Rothermel 1983, Chandler and others 1991, Simard 1991, Hungerford 1996, Debano and others 1998, Robichaud and others 2003).

Composition, moisture content, amount, and structure (size, distribution, depth, soundness, age, and so forth) of wildland fuels influence how they burn and how the fire affects the environment (Albini and Reinhardt 1995, Agee and others 2002). Physical setting and short-term weather (daily to weekly temperature, relative humidity, wind, and precipitation cycles) have the most immediate influence on fire behavior, but long-term weather (droughts) and location can influence wildfire occurrence and subsequent behavior (Chandler and others 1991, Rothermel 1991, Agee 1998b, Bradshaw and others 2003). Landforms (physical setting) and climatic variations produce a diverse mixture of forest types that span a gradient from wet, dense, coastal forests to arid interior forests (Daubenmire and Daubenmire 1968, Steele and others 1983, Cooper and others 1991, Perry 1994). Climatic patterns, especially magnitude and distribution of precipitation, can influence natural disturbances and in particular wildfire (Agee 1993, Veblen and others 2000, Hessl and others 2003).

Fire regimes (characteristics of fire such as the intensity, frequency, season, size, and extent that create particular fire effects in a biogeographical region) can be altered by fire exclusion and land management practices. In the Western United States, alteration of fire regimes by fire exclusion has been greatest in dry forests, primarily those dominated by ponderosa pine, Douglas-fir, or both (Covington and Moore 1994, Arno and others 1997, Swetnam and others 1999, Romme and others 2003). Millions of acres of forestlands in the Western United States contain a high accumulation of flammable fuels compared to fuel conditions prior to the 20th century, which in turn have posed an increasing fire hazard for many decades (Skinner and Chang 1996, Covington and Moore 1994, Arno and others 1997, Hann and others 1997, Swetnam and others 1999).

The large and destructive wildfires in the summers of 2000 and 2002 and autumn of 2003 have sharpened our focus on fuel accumulation on the National Forests and other public lands. During the summer of 2000, 122,827 wildfires burned 8.4 million acres, and during the summer of 2002, 73,457 fires burned 7.1 million acres (http://www.nifc.gov). Such severe and large wildfires put a number of important values at risk as exemplified by the destruction of more than 3,600 homes in the wildfires that burned in southern California in 2003. Although homes in the path of a wildfire are perhaps the most immediately recognized value at risk, there are numerous other values at risk including critical infrastructure (power grids, drinking water supplies), sensitive or protected fish and wildlife habitat, firefighter health and safety, public health and safety, soil productivity, aesthetics, clean air, and other important components of forest ecosystems (Weaver 1943, Reynolds and others 1992, Covington and Moore 1994, Covington and others 1997, Fulé and others 1997, Swetnam and others 1999, Conard and others 2001, Kalabokidis and others 2002, Cohen and Stratton 2003). Some of these values are also threatened by secondary effects of a severe wildfire, such as landslides, spread of invasive species, and wind throw (Robichaud and others 2000).

Historical Fire Patterns and Forest Structure

Prior to reductions in burned area during the 20th century, temperature, and precipitation patterns, combined with natural and human ignitions, were most responsible for determining fire return intervals (also referred to as fire frequency), particularly in the dry ponderosa pine and Douglas-fir forests. Before Euro-American settlement, cultural burning practices of Native Americans augmented or even dominated fire regimes in many vegetation types (Barrett and Arno 1982, Stewart 1951, Lewis 1973). Lightning-caused fires were more frequent during periods (decades) of high temperatures and became less frequent during cool periods because warm periods tended to have longer fire seasons, resulting in more fires (Swetnam 1993, Stine 1996, Chang 1999). The variation in precipitation from year to year affected the availability of grass and herbaceous surface fuel and the duration of windy or dry burning conditions. Moist years allowed rich layers and amounts of forest vegetation to develop especially in the form of grasses, shrubs, and other ground-level vegetation. In Southwestern ponderosa pine forests where grass fuels predominated before Euro-American settlement, periods with abundant precipitation supported the development of high fuel loads, which supported the more widespread fires that tended to occur in dry years that occurred intermittently throughout wet periods (Swetnam 1993). By contrast, periods of low precipitation supported smaller, less widespread fires (Swetnam 1993, Chang 1999). Where grass and herbaceous surface fuels are not dominant (for example, ponderosa pine and mixed conifer forests of the Sierra Nevada), fire sizes were generally fuel limited except when affected by regionwide droughts (Swetnam 1993). These variations in weather produced variable fire frequencies in many of the dry ponderosa pine and Douglas-fir forests of the West. For example, in a portion of the Colorado Front Range of the Rocky Mountains, the fire frequency, determined by tree ring analysis, varied considerably over the past 700 years, ranging from relatively frequent (16.8 year interval) fires to moderate fire intervals to one long interval (more than 50 years) (Kaufmann and others 2001).

Based on tree-ring data, the 20th century has been described as a period of relatively high precipitation and increasing temperature compared to previous centuries (Briffa and others 1992, Graumlich 1993, Stine 1996). Stine (1996) suggests that more frequent and larger fires, characteristic of the latter portions of the 20th century, were the result of warm temperatures that likely lengthened the fire season, and the increased precipitation allowed fuels to accumulate. Yet, fire exclusion through fire suppression or reduction of fine fuels through grazing, urbanization, and other land use changes particularly in the dry ponderosa pine and Douglas-fir forests, caused a dramatic reduction in the area burned by frequent fires. In turn, these and other past management activities resulted in significant changes since the late 1800s in the structure of forest stands (contiguous vegetation containing the same forest structure and composition occurring on a common environmental site) (Helms 1998). Most likely, the greatest changes in stand structure from those occurring historically, occurred on productive sites where vegetation readily developed (Weatherspoon and Skinner 1996).

Forest Change

Prior to the 20th century, low severity fires burned regularly in most dry forest ecosystems (Covington and Moore 1994, Arno and others 1997, Swetnam and others 1999, Everett and others 2000, Hessl and others 2003), with ignitions caused by both lightning and humans. Low intensity fires controlled regeneration of fire-intolerant (plants unable to physiologically withstand heat produced by fires) species, promoted fire-tolerant species (for example, ponderosa pine and Douglas-fir), maintained an open forest structure, reduced forest biomass, decreased the impacts of insects and diseases (Covington and Moore 1994, Weaver 1943), and maintained wildlife habitats for many species that utilize open stand structures (for example, northern goshawk) (Reynolds and others 1992, Fulé and others 1997, Swetnam and others 1999, Conard and others 2001, Kalabokidis and others 2002). In addition to the accumulation of fire intolerant vegetation, dense forest canopies with homogeneous and continuous horizontal and vertical stand structures (for example, dense trees with low crown base heights) developed resulting in an increased potential for crown fires in many forests of the Western United States (Cooper 1960, Dodge 1972, Van Wagner 1977, Parsons and DeBenedetti 1979, Bonnickesen and Stone 1982, Arno and Brown 1991, Agee 1993, Mutch and others 1993, Hann and others 1997) (fig. 1). These changes in structure and composition have dramatically altered how wildfires now burn in these forests from how they burned historically.

Historically, 40 percent of the forests in the United States were burned by frequent (0- to 35-year intervals) low-severity fires (fire regime 1), but only

1909

1948

1989

Figure 1—Forest development on the Bitterroot National Forest in Montana in a ponderosa pine stand after harvest (1909) in which fire was excluded since 1895. Note the changes in vertical arrangement and horizontal continuity in forest stand structure. In general many of today's ponderosa pine forests contain higher densities of fire-intolerant species and suppressed trees than historical forests.

15 percent are currently burned by these kinds of fires. Mixed fire regimes, characterized by 35- to 100-year fire return intervals, and a mixture of low to moderate surface fires and higher severity stand replacement fires, historically occurred on about 40 percent of forested areas. They currently occur on about 35 percent of the forested areas (Schmidt and others 2002). As a result of these current conditions, more than 80 percent of the forest landscape in the inland Northwestern United States contains lands with mixed to high severity fire regimes (Quigley and others 1996) (fig. 2).

The greatest changes in ponderosa pine and dry Douglas-fir forests have occurred predominantly in fire regimes characterized historically by high frequency surface fires (Arno 1980, Agee 1991, 1993, 1994, Taylor and Skinner 1998, Brose and Wade 2002). Weaver (1943) noted that historically, dry forests contained diverse understories most often of grasses, forbs, and low shrubs—a condition maintained by frequent, low-intensity surface fires. These forests were so open Western settlers were able to travel through many of the pine stands on wagons and horseback (Evans 1990, Wickman 1992) (fig. 3). Dense stand and forest structures are now common on sites historically burned by frequent, low to moderately severe fires (Arno 1980, Agee 1991, 1993, 1994, Taylor and Skinner 1998, Brose and Wade 2002). These conditions— with their abundant surface and ladder fuels, and low canopy

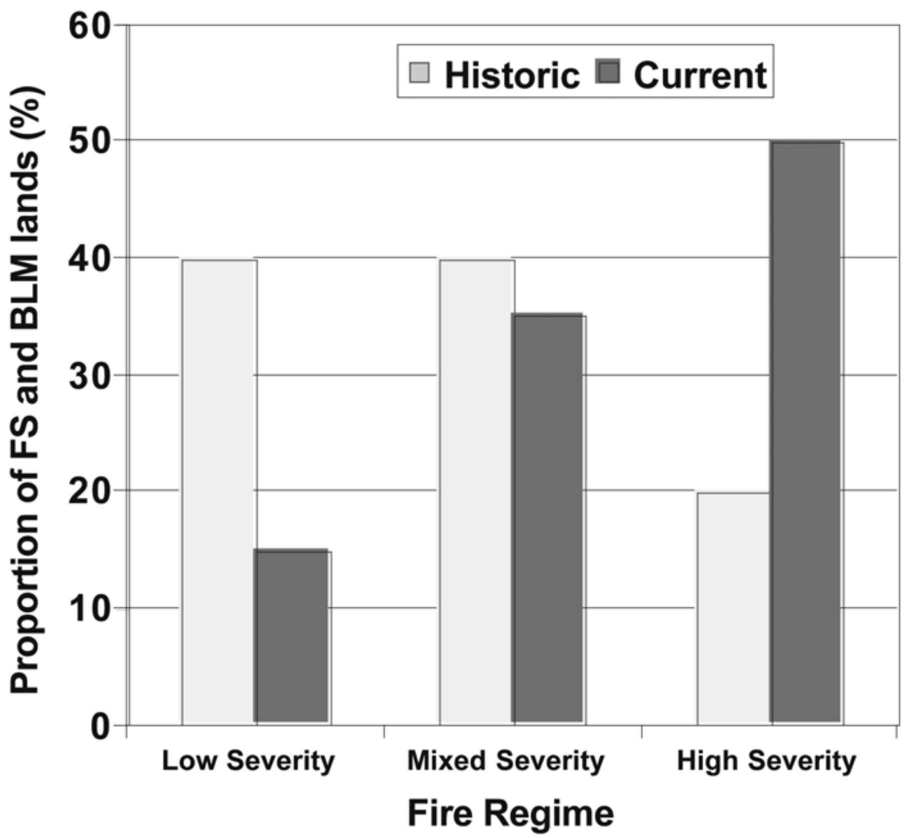

Figure 2—The proportion of low severity, mixed severity, and high severity fire regimes in the pre-1900 period and in recent times in the inland Northwestern United States. Note the increasing proportion of high severity fire regime. Data from Quigley and others (1996).

Figure 3—Historically (1900) open ponderosa pine conditions were probably maintained by frequent surface fires. Note the abundant grass layer and the relatively high crown base heights.

base heights—readily facilitate the development of crown fires (Weaver 1943, Dickman 1978, Laudenslayer and others 1989, Scott and Reinhardt 2001) (fig. 1).

Throughout the United States, wildfires have been aggressively suppressed since the early 1900s, although this effort has likely been most successful only after about 1940 when modern vehicles and equipment became available and extensive road networks made remote locations accessible. In the Western United States, the area annually burned decreased from the early 1900s into the 1960s, then the trend reversed, with the number of acres burned each year increasing with significant increases since the mid-1980s (Agee 1993). This was exemplified by the fires that burned in and around the Bitterroot National Forest in 2000 (fig. 4). What appears to be different about the recent fires is the number of ignitions that contributed to burning large areas. More than 1,700 fire starts were responsible for burning the 3.1 million acres of the Northern Rocky Mountains in 1910, and 78 starts burned more than 350,000 acres in the Bitterroot Valley in western Montana in July 2000 (USDA Forest Service 1978, 2000). Contrast these fire events to the 2002 Rodeo-Chedeski Fire that was the result of only two fire starts and burned more than 450,000 acres in Arizona. Similarly, on June 8, 2002, one start along the Colorado Front Range of the Rocky Mountains led to the Hayman Fire that burned nearly 138,000 acres in 20 days (Graham 2003). These recent and large wildfires all seem to exhibit uncharacteristically intense wildfire behavior and increased fire severity (fig. 5).

Figure 4—One of the many fires that burned in the Bitterroot Valley of western Montana in 2000.

Figure 5—Uncharacteristically intense wildfire burning a current ponderosa pine dominated forest. Note the low crown base heights and the intense surface fire.

Fuels

Fire behavior and severity depend on the properties of the various fuel (live and dead vegetation and detritus) strata and the continuity of those fuel strata horizontally and vertically. The fire hazard for any particular forest stand or landscape can be characterized by the potential for the fuels to cause specific types of fire behavior and effects. Understanding the structure of fuelbeds and their role in the initiation and propagation of fire is the key to developing effective fuel management strategies.

Fuelbeds are classified in six strata: (1) tree canopy, (2) shrubs/small trees, (3) low vegetation, (4) woody fuels, (5) moss, lichens, and litter, and (6) ground fuels (duff) (Sandberg and others 2001) (fig. 6). 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 severity (fig. 5).

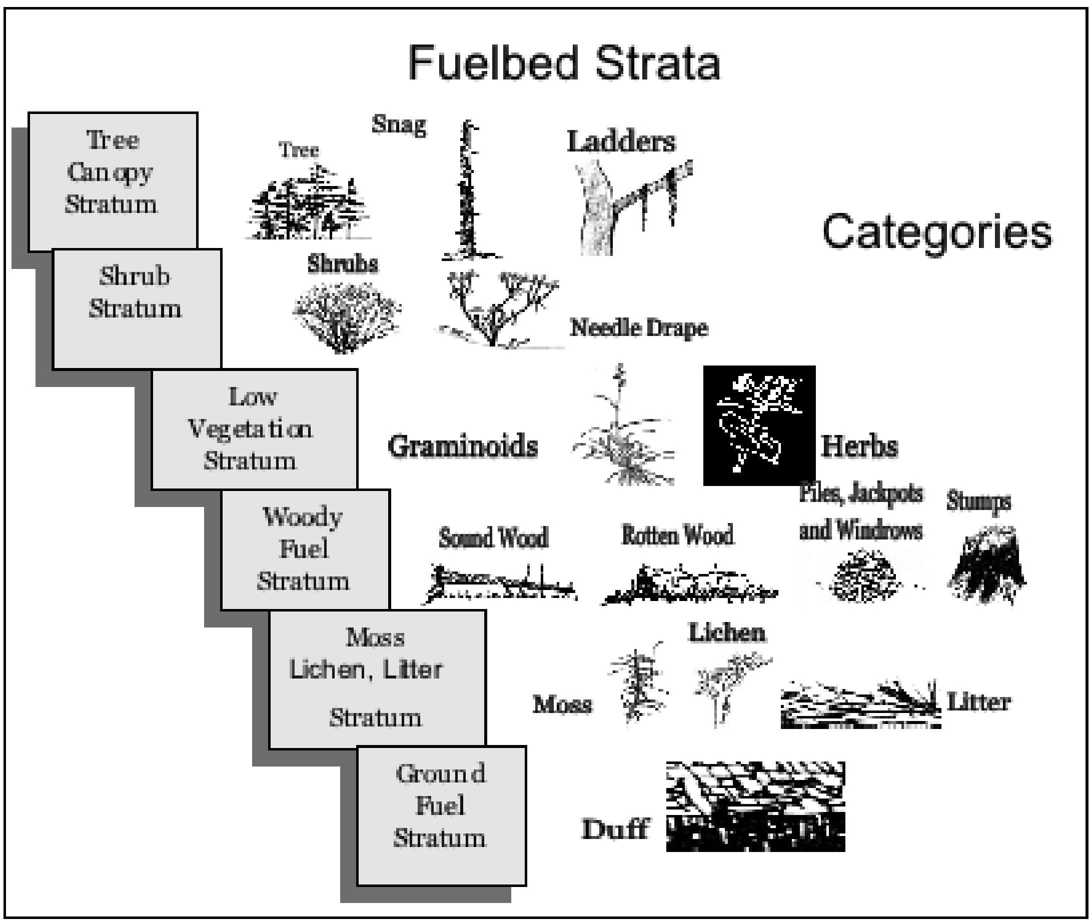

Figure 6—Six horizontal fuelbed strata represent unique combustion environments. Each fuelbed category is described by physiognomic (qualitative features including morphological, chemical, and physical features) and relative abundance (Sandberg and others 2001).

- Ground fuels consist of duff (organic soil horizons), roots, and buried woody material (fig. 7) (Sandberg and others 2001). Often needle fall and bark slough will accumulate at the base of trees and eventually create deep organic layers in which fine roots and ectomycorrhizae of trees and ground level vegetation may accumulate (Graham and others 2000). Ground fuels burn typically by smoldering and may burn for many hours, days, or even weeks, if initial moisture contents are high (Frandsen 1991, Hungerford and others 1991) (fig. 7). This long duration smoldering can often lead to soil damage, tree mortality (high severity), and smoke impacts (Wells and Campbell 1979, Ryan and Noste 1983, Ryan and Reinhardt 1988). Rotten material on the ground surface is particularly ignitable by firebrands (small twig segments or bark flakes supporting glowing combustion) falling ahead of an advancing fire front, which increases the success of spotting (fig. 7).

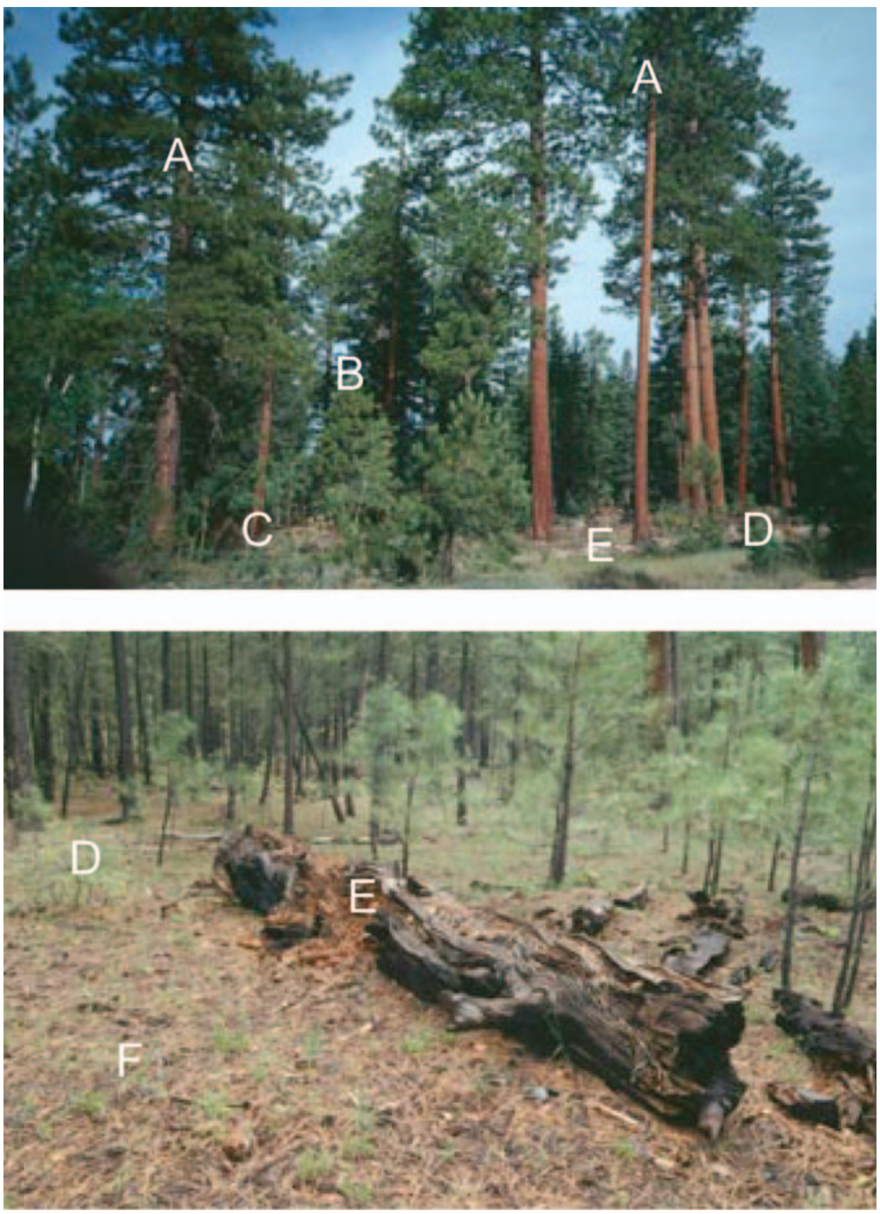

Figure 7—Fuelbed strata have different implications for combustion environment, fire propagation and spread, and fire effects. The canopy (A), ladder fuels (B) and shrub layers (C) contribute to crown fires. Low vegetation (D), woody fuel (E), and ground fuel (F) contribute to surface fires. Woody fuel (E) and ground fuels (F) are most often associated with smoldering fires and residual combustion that can transfer large amounts of heat deep into the soil.

- Surface fuels consist of grasses, shrubs, litter, and woody material lying on, or in contact with the ground surface (fig. 6, 7) (Sandberg and others 2001). Surface fuel bulk densities (weight within a given volume), and size class distribution (for example, number of pieces in 0 to 0.25 inch, 0.25 to 1.0 inches, 1.0 to 3.0 inches, and greater than 3 inches size classes) are critical to frontal surface fire behavior (spread rate and intensity) compared simply to fuel loading (weight per unit area). Other characteristics of surface fuels that determine surface fire behavior are fuel depth, continuity, and chemistry (fig. 8). Surface fires burn in both flaming and postfrontal (smoldering or glowing—minimal flames but glowing embers) phases. High energy release rates occur during the relatively short flaming phase where fine fuels are consumed, and low energy release rates occur for longer times by smoldering and glowing phases that consume larger (greater than 3 inches diameter) fuels. Surface fuel complexes with high loadings of large material—for example, slash left after timber harvesting, precommercial thinning operations, or high fuel loads from natural events such as blowdowns or ice storms—have long flaming residence times compared to fine fuels such as shrubs or grasses. High surface fire intensity usually increases the likelihood for igniting overstory canopy fuels, but surface fuel types with longer residence times can contribute to drying aerial

Figure 8—Reducing the amount, depth, and continuity of surface fuels, especially those less than 3 inches in diameter, left after forest management activities using prescribed fire or mechanical methods reduces the likelihood that overstory canopies will ignite during a wildfire.

fuels above a forest canopy, which also leads to torching (when a tree's or group of trees' foliage ignites and flares up, usually from bottom to top) (Alexander 1998).

- Crown fuels (also referred to as canopy fuels, or aerial fuels) are those suspended above the ground in trees or vegetation (vines, mosses, needles, branches, and so forth) (fig. 6, 7). These fuels tend to consist mostly of live and fine material less than 0.25 inch. Crown fuels are the biomass available for crown fire, which can be propagated from a surface fire via understory shrubs and trees, or from crown to crown. 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 facilitating crown fires. These essentially bridge the vertical gap between surface and crown strata. The size of this gap is critical to ignition of crown fire from a surface fire below (Van Wagner 1977). Van Wagner (1977) identified two thresholds of crown fire activity. Crowns are ignited after the surface fire reaches critical fireline intensity relative to the height of the base of the aerial fuels in the crown. This crown ignition can become an "active" crown fire if its spread rate is high enough to surpass the second threshold based on the crown density (often referred as canopy bulk density—canopy weight for a given volume). Aerial fuels separated from surface fuels by large gaps are more difficult to ignite because of the distance above the surface fire, thus requiring higher intensity surface fires, surface fires of longer duration that dry the canopy before ignition, or mass ignition from spotting over a wide area (Byram 1966) (fig. 9). Once ignited, high density canopy fuels (fig. 7A) are more likely to result in a spreading crown fire (active crown fire) than low density canopies.

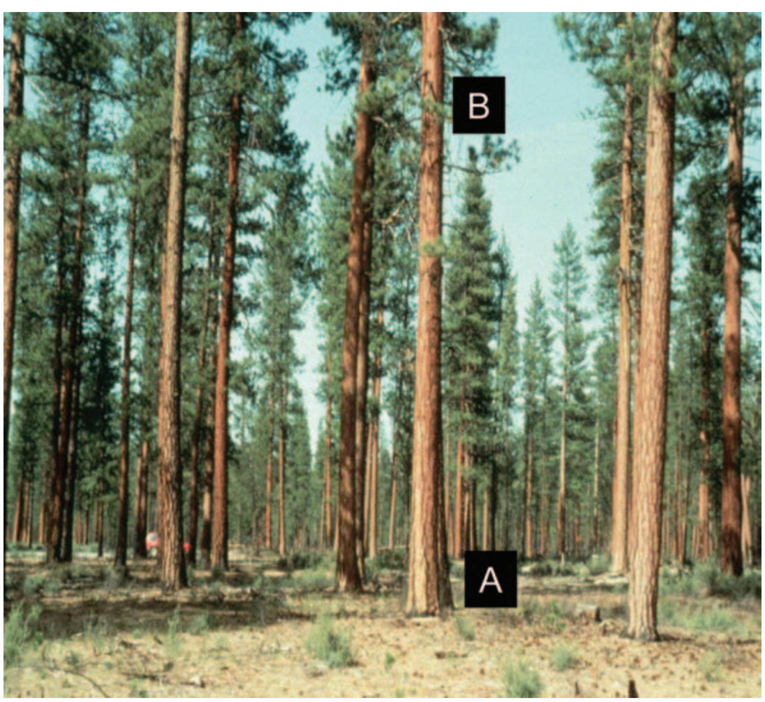

Figure 9—The greater the distance between surface fuels (A) and the base of tree crowns (B) the more difficult it is for surface fires to become crown fires.

Conditions for Ignition

The probability of ignition is strongly related to fine fuel moisture content, air temperature, the amount of shading of surface fuels, and the occurrence of an ignition source (human or lightning caused) (Rothermel 1983). Stand structure strongly influences all these factors. There is generally a warmer, dryer microclimate in more open stands (fig. 9) compared to denser stands (fig. 7A) (Countryman 1955, Weatherspoon 1996). Dense stands (canopy cover) tend to provide more shading of fuels, keeping relative humidity higher and air and fuel temperature lower than in more open stands. Thus, dense stands tend to maintain higher surface fuel moisture contents compared to more open stands (Andrews 1986). More open stands also tend to allow higher wind speeds that tend to dry fuels compared to dense stands (Weatherspoon 1996). These factors may increase probability of ignition in some open canopy stands compared to dense canopy stands. However, this forest structure historically played an important role in maintaining fire-dependent forest types, such as ponderosa pine.

Fire Behavior

In general, wildfire behavior is influenced by short- and long-term weather, physical setting (local to regional topography and terrain features), fuels (composition, structure, moisture content of dead and live vegetation and detritus) (Rothermel 1983, Chandler and others 1991, Debano and others 1998, Graham and others 1999). All of these elements work in concert over multiple spatial and temporal scales to determine how wildfires behave. Because of the infinite number of combinations of these elements, as well as ignition location, the growth and behavior of each fire are likely to be unique. Most important, the fire behavior characteristics are strikingly different for cold (for example, lodgepole pine, Engelmann spruce, subalpine fir), moist (for example, western hemlock, western redcedar, western white pine), and dry forests (Agee 1993, 1996, 1998b, Romme and others 2003). Cold and moist forests tend to have long fire-return intervals, but fires that do occur tend to be high-intensity, stand-replacing fires. Dry forests historically had short intervals between fires, but most important, the fires had low to moderate severity.

Fire behavior is typically described at the stand level, but the spatial arrangement of stands affects the growth of large fires across landscapes. Fire behavior characteristics include rate of spread, intensity, residence time, transition to crown fire, and spotting, and are associated with a flaming front (Rothermel 1972, 1983, 1991, Albini 1976, VanWagner 1977). Typically these are defined, modeled, and measured at the head of a fire (burns with the wind or slope) but can apply to any segment of fire perimeter spreading in any direction such as a flanking (tangential to the direction of the main active fire, generally across slope) or backing (opposite the direction of the main active fire, generally downslope) fire. These behaviors usually apply to fine spatial scales (hundreds to thousands of square feet), and time intervals of less than a minute to tens of minutes. However, considerable variation within those periods can be exhibited. In many fires, fuel consumption and smoke production occur in both flaming and smoldering postflaming phases of combustion, with most consumption of, and smoke production from, woody fuel and ground fuel strata occurring after flaming has ceased (Frandsen 1991, Hungerford and others 1991) (fig. 10).

Frontal fire behaviors in broad landscapes vary at coarser temporal (for example, days) and spatial scales as the fire moves across various stands, terrain, and fuel conditions. Fire behavior in landscapes is often described in terms of perimeter or area growth (Rothermel 1991). Ember production from torching trees and crown fire can rapidly advance the fire front, increasing its growth and allowing it to cross natural or artificial barriers (Albini 1979). The relative spread direction (backing, flanking, heading) is an important aspect of fire behavior because fires interact with vegetation, weather, and setting to back and flank around different situations as they move through a landscape. Fires are usually placed into three broad classes, each containing unique fire behavior characteristics. These fires include smoldering or ground fires, surface fires, and crown fires.

Ground Fire

Ground fires or residual smoldering fires, are an important but often overlooked component of most fires (Frandsen 1991). Three fuelbed strata contribute to the initiation and slow spread of ground fires (fig. 7, 8, 10). Ground fuel, consisting principally of soil organic horizons (or duff), contributes most of the fuel and can burn slowly for days to months even if the fuels

Figure 10—Large amounts of smoke can be produced from smoldering ground fuels after flames have subsided and large amounts of heat can be transferred to the soil (K. Watenmaker photo).

are relatively wet (fig. 7F). Deep layers of continuous ground fuels 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 ground fires and a transition to surface (flaming) fire. Woody fuel (sound logs, rotten logs, stumps, and wood piles) is often underestimated as a component of ground fires but can sustain low intensity burning for weeks to months, with potential flaming combustion under dry, windy conditions (fig. 7E). Combustion of woody fuel also can contribute significantly to smoke production and soil impacts (for example, loss of organic matter, erosion, nutrient volatilization) (Hungerford and others 1991, Johansen and others 2001) (fig. 10).

Surface Fire

The intensity and duration of surface fires depend on the availability and condition of surface fuels. Three fuelbed strata (low vegetation, woody fuel, and moss, lichen, and litter) contribute to the initiation and spread of surface fires (fig. 6, 7). These materials can be randomly distributed across the forest floor or may be concentrated in piles created through management activities or naturally occurring events (for example, wind-thrown trees). Woody fuel can greatly increase the energy released from surface fires and in some cases increase flame lengths sufficiently to ignite ladder and/or canopy fuels (fig. 11). Especially in the dry ponderosa pine and Douglas-fir forests, forest floor litter consisting of small twigs, dead needles,

Figure 11—With sufficient fuels and flame lengths (fire intensity) surface fires can ignite ladder fuels and tree crowns (K. Watenmaker photo).

and rotten wood can also increase the energy released during surface fires (fig. 6, 7). Both burning and fuel conditions of surface fuels are highly influenced by the presence and density of overstory tree canopies. Fine fuel moisture content, surface air temperature, and shading of surface fuels contribute to increasing the spread rate of surface fires in open stands compared to surface fires burning in dense stands (Rothermel 1983, Andrews 1986). Additionally, open conditions facilitate the development of fine fuels (grasses, forbs, small shrubs) more readily than dense stands (fig. 3), and when continuous these fine fuels can support more rapid fire spread compared to large woody fuels. When surface fires frequently burn, they tend to minimize surface and ladder fuel accumulations, which in turn decrease the likelihood that crown fires will develop. Low severity surface fires were relatively common (4 to 25 years) in the dry ponderosa pine and Douglas-fir forests prior to the 20th century (Agee 1993, Hann and others 1997).

Crown Fire

The spatial continuity and density of tree canopies in combination with wind and physical setting provide the conditions required for rapidly moving fires that typically consume the crowns (needles and small branches) of large forest areas (fig. 6, 7). Canopy base height, canopy bulk density (canopy weight for a given volume), and canopy continuity are key characteristics of forest structure that affect the initiation and propagation of crown fire (fig. 7A) (Albini 1976, Rothermel 1991). Canopy base height is important because it affects crown fire initiation (fig. 9). Continuity of canopies is more difficult to quantify, but clearly patchiness of the canopy will reduce the spread of fire within the canopy stratum. Forest treatments that target height to live crown and bulk density can be implemented to reduce the probability of crown fire. Canopy bulk density varies considerably within stands but can reach maximum values of 0.4 kg m^{-3} (Cruz and others 2003). Thinning to reduce canopy bulk density to less than 0.10 kg m^{-3} is generally recommended to minimize crown fire hazard (Agee 1996, 1998b, Graham and others 1999), and for the most part below this point, active crown fire is difficult to achieve (Scott and Reinhardt 2001).

Wildfires often exhibit sporadic crown fire development with fast and slow episodes of fire growth. Along with wind and fuels, the relative humidity of the air can have a large affect on fire behavior. For example, the 2002 Hayman Fire in Colorado experienced rapid growth and intense behavior on days when the humidity hovered in the 10 percent range (Bradshaw and others 2003, Finney and others 2003). Fire behavior on these days took place during prolonged burning periods (daily periods of active fire behavior) that lasted from mid-morning to nearly midnight and that characteristically had torching, spotting, and crown fire (Finney and others 2003). When the relative humidity was more moderate (exceeding 10 percent) the Hayman Fire behavior was typified by surface fire, although some tree torching and crown fire occurred.

Surface fires can spread rapidly through dry grass and forest floor fuels igniting tree crowns (especially those with low crowns). Torching often progresses from individual trees and small groups of trees to large groups and stands within a few hours (fig. 12). Torching and crown fire are strongly associated with spotting because firebrands are produced and injected high into the windstream by vertical convection above the flame plume (Albini 1979). Winds often carry firebrands hundreds of feet and even miles from their sources spanning barriers such as roads, ridges, rivers, and rock outcroppings. Subsequent and numerous ignitions often occur when the humidity is low and receptive, and when dry and continuous surface fuels exist. This process can be repeated numerous times because fires can move many miles in a day (Finney and others 2003). Over time, fire fronts can increase in both number and size and interact with topography that further contributes to crown fire runs. Entire stands and hillsides can be simultaneously ignited, which further advances fires by spotting. Under these extreme weather conditions, long-range spotting (0.5 to 0.75 mile) can accelerate fire intensity and spread. Fires can travel 1 to 2 miles per hour (88 to 176 feet per minute) and produce flame lengths from 100 to 200 feet during crown fire spread. These kinds of fire behavior are typically associated with atmospheric instability with vertical contrasts of temperature and humidity. These conditions often develop above large fires producing large pyrocumulus

Figure 12—Fires can progress from torching individual and groups of trees until entire hillsides are a blaze (K. Watenmaker photos).

clouds (Werth and Werth 1998, Finney and others 2003) (fig. 13). These kinds of extreme wildfire behaviors are not well understood, and their associated fire whirls (Byram and Martin 1970) and mass ignition (Byram 1966, McRae and Stocks 1987) can create tremendous local convective velocities and burning rates beyond the scope of operational fire behavior or fire effects models.

Other Influences on Fire Behavior

Fuels, weather, and physical setting determine fire behavior and in particular determine fire intensity (the rate at which a fire produces thermal energy in the fuel-climate environment). Therefore, the relation forest structure has with fire intensity depends on the setting at which the fire occurs, and on weather. The attributes of weather and physical settings that constrain fire behavior occur at multiple spatial and temporal scales. Weather at small spatial (forest stands and drainages) and temporal (hours) scales regulates fuel moisture content, which influences diurnal and day-to-day variation in fuel flammability. Temperature, relative humidity, and wind throughout the fire season determine fire danger and the potential for flammability and fire spread during wildfires. Weather at broad spatial (regions, multiple states) and temporal scales (months to years), or climatology, influences the availability of fuel over time and often controls extreme fire behavior (for example, crown fire spread) and the occurrence of large fires (Turner and others 1994, DellaSala and others 1995), although this generalization varies considerably among biogeographic regions. Extreme fire weather (low humidity and strong winds) also played a significant role in the

Figure 13—Pyrocumulus clouds can develop high (20,000 feet) over wildfires carrying particulates and carbon monoxide.

1988 Yellowstone Fires (subalpine fir and lodgepole pine forests) (Romme and Despain 1989) and in the Hayman Fire (ponderosa pine and Douglas-fir forests) in Colorado in 2002 (Finney and others 2003) (fig. 11, 13).

Elevation, slope angle, aspect, and physiographic position influence how a fire behaves (Agee 1993). At the broadest scale the orientation of river corridors and/or mountain ranges influences how wind and precipitation develops, and topographical features such as mountain passes can funnel winds. In general, as elevation increases both precipitation and humidity increases and temperature decreases, and these factors influence a fire's behavior as it burns up or down slopes. Fuels occurring on south-facing aspects tend to be drier and dry faster (annually and diurnally) than fuels occurring on northerly aspects. Fire spread rates double for every 30 percent increase in slope angles up to 60 percent and doubles for every 15 percent increase thereafter (Chandler and others 1991). Fires burning in narrow V-shaped canyons may radiate sufficient heat to opposite slopes, thereby predrying fuels, which can enhance a fire's spread. Also, this canyon configuration can channel winds spreading burning fire brands to opposite canyon walls. Depending on the ridge and canyon configuration, there tends to be a zone of turbulence when strong winds blow across ridges, which can radically influence fire behavior (Chandler and others 1991). Therefore, there are times when weather and physical setting control fire behavior, with forest structure having minimal effect.

Depending on the type of fire (crown, surface, or smoldering) the interaction between weather, physical setting, and fuels will vary. For example, Hely and others (2001) compared BEHAVE (surface fire model) and the Fire Behavior Prediction (FBP) model (crown fire model) using Canadian mixed wood boreal forests. Their results disclosed that the dominant factor when describing fire behavior using the FBP system was weather, whereas using BEHAVE, surface fuels were more important in explaining the variation in fire. Bessie and Johnson (1995) evaluated the surface fire intensity relations in BEHAVE to determine the relative roles of fuel and weather in subalpine forests of the Southern Canadian Rocky Mountains (Rothermel 1972, Van Wagner 1977). They determined that surface fire intensity and crown fire initiation were constrained by weather rather than fuels, while crown spread was slightly more dependent on fuels. These studies indicate that the relative influence of weather and fuels varies as a function of the specific biophysical conditions.

The Hayman Fire in Colorado provides a good example on how the combination of factors (weather, forest structure, physical setting) occurring at multiple spatial scales influence how a wildfire burns (Bradshaw and others 2003, Finney and others 2003). At the broad scale, a low pressure system centered in eastern Washington influenced the wind direction and local weather conditions occurring along the Front Range of the Rocky Mountains. The landscape position of the South Platte River corridor readily aligned with strong winds generated by the low pressure system along with local dry air masses (humidity below 10 percent); combine this location with the continuous dry fuels (ponderosa pine and Douglas-fir forests), and an ignition in the right location led to rapid wildfire spread. This combination of fuels, weather, and topography led to a fire run of 16 to 19 miles lasting an entire day, burning 60,000 acres. Under these burning conditions fine-scale forest structural variability (for example, stand density and composition) that may have altered fire behavior under more benign weather had little effect on fire progression. Islands of stands where fuels had been modified were often surrounded by large extents of forest with heavy ladder fuels and high crown densities. As a result, while the Hayman Fire behavior and severity were affected locally, these fuel modifications did little to influence the overall behavior and severity of the fire (Finney and others 2003).

Fire Severity and Fire Effects

Each fuelbed and combustion environment can create a different fire severity (Ryan and Noste 1983). Crown fires remove much or the entire tree canopy in a particular area, essentially resetting the successional and growth processes of stands and forests (fig. 14). These fires typically, but not always, kill or temporarily reduce the abundance of understory shrubs and

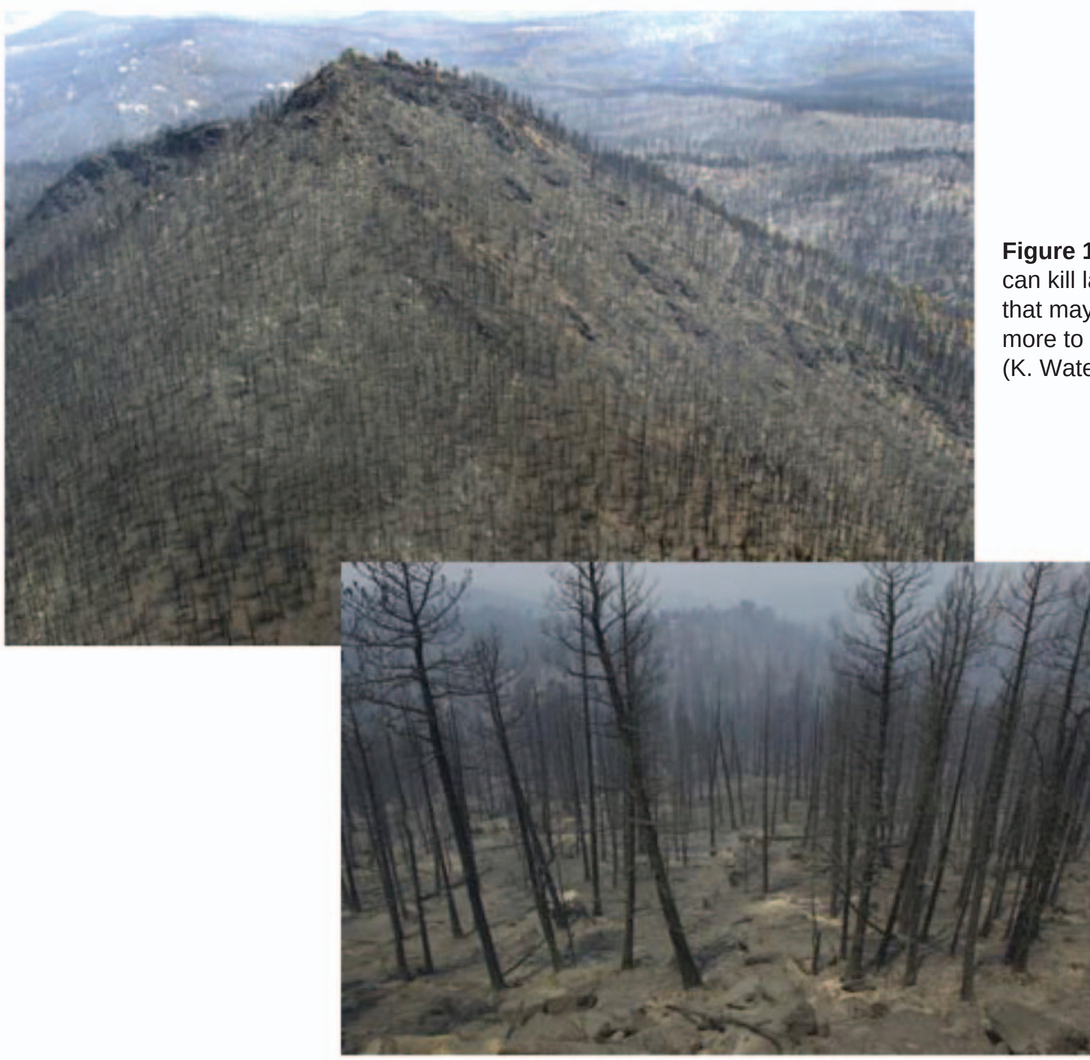

Figure 14—Severe crown fires can kill large expanses of forests that may take a 100 years or more to return to a prefire state (K. Watenmaker photos).

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 and woody, moss, lichens, and litter strata. This temporarily reduces the likelihood of future surface fires propagating into crown fires. Ground fires that consume large amounts of woody fuels and organic soil horizons can produce disproportionately large amounts of smoke (fig. 10). 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. These fires can also damage and kill large trees by killing their roots and the lower stem cambium (Swezy and Agee 1991). Because ground fires are often of long duration, they may result in greater soil heating than surface or crown fires, with the potential for reducing organic matter, volatilizing nutrients, and creating a hydrophobic layer that contributes to erosion (Hungerford and others 1991, Johansen and others 2001, Robichaud and others 2003) (fig. 15).

Figure 15—Ground fires (especially those with long residence times) can severely burn soils, removing organic matter, volatilizing nutrients, killing tree roots, and creating water impermeable layers (see fig. 7, 10).

Dense forest conditions combined with extreme fire weather conditions can lead to high fire severity in Western forest landscapes. Areas where organic matter is entirely burned off may not return to the prefire state for decades or centuries, but water repellent soil layers are usually more ephemeral, persisting for 2 to 6 years (Johansen and others 2001) (fig. 16). Areas where the ground cover is removed and severely burned will likely see decreased infiltration of water, increased surface runoff and peak flows, and

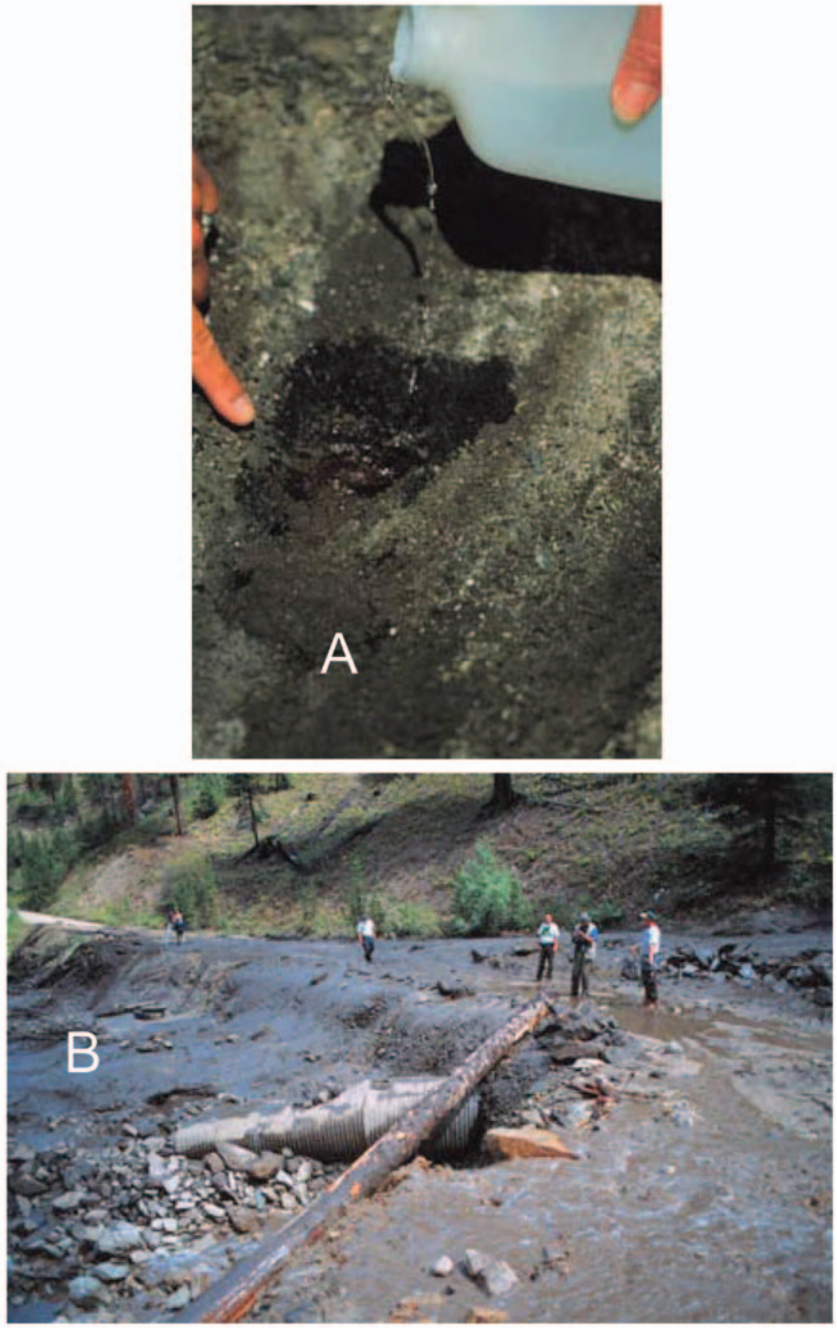

Figure 16—Water repellent soil layers (A) after wildfires can promote soil erosion (B), which in turn can impact domestic water supplies, decrease site productivity, and slow vegetative recovery (K. Watenmaker photos).

the formation of pedestals, rills, and gullies (Johansen and others 2001). In riparian settings the recovery of hillslopes and riparian vegetation will influence how quickly the aquatic environments recover. Clearly, areas that are less severely burned will likely recover to prefire conditions most rapidly. Recovery of aquatic ecosystems within severely burned watersheds will be most dependent on riparian recovery and the proximity to high quality habitats that can provide sources for recolonization (Cipra and others 2003, Romme and others 2003).

Depending on the setting (in particular topography and soil), perennial streams downstream from fires can be impacted by large volumes of sediment (fig. 16). Depending on the recovery of the hillslopes, these fire effects can be long lasting, and relatively little can be done to stop the problem. Large amounts of sediment can be delivered into reservoirs, reducing water storage capacity and potentially affecting fish and macroinvertebrate habitat. However, many ecosystems have a long history of fire, and native species and populations have developed mechanisms for enduring fire or becoming reestablished after fire. Therefore, most often the terrestrial vegetation will likely recover normally. Where prefire vegetation is dominated by sprouting species (for example, aspen, cottonwood, many shrub species, many grasses, and other herbaceous species), a rapid return to prefire conditions is generally expected (Cipra and others 2003).

Areas dominated by nonsprouting species (for example, most conifer species in dry interior forests), and areas burned by low-severity fires that do not kill the entire forest canopy, may rapidly return to prefire conditions. In areas where fires burn with moderate severity and also contain small patches of high-severity burn, tree seedlings will most likely become established within several years. Areas with large patches of high-severity fire may become reforested slowly because of high local seed mortality and long distances to seed sources outside the burned area; planting or seeding can speed up regeneration in these cases (fig. 14). Fire facilitates the spread of exotic species in most dry interior forests, and exotic species in turn can alter fire regimes, nutrient cycling, and hydrology. Exotic plant species typically persist in riparian and drainage areas, open-canopy areas, and along disturbance corridors such as roads and trails (Galley and Wilson 2001, Cipra and others 2003, Romme and others 2003), and most species are difficult to control.

Fuel Modifications

In this section we describe the range of treatments that can be used to modify forest fuels (vegetation), but we do not attempt to provide indepth prescriptions for their implementation. Depending on the forest type and physical setting, high densities of tree seedlings can regenerate after disturbance (Haig and others 1941, Pearson 1950), but as forests naturally develop, tree numbers would decrease (fig. 1, 3). This reduction is caused by intertree competition, wind, snow, ice, diseases, insects, fire, or a combination of these factors. In addition to natural events that reduce density of forest stands, forest management through the application of thinnings also can alter species composition and stand structure. Classically, the term "thinning" was applied to stand treatments aimed at redistributing growth on remaining stems, but often any kind of partial cutting such as cleaning, weeding, liberation, preparatory, improvement, sanitation, and selection cuttings could be termed thinning. In all cases these treatments reduce the numbers of stems in a forest stand and can create an infinite number of stand structures (Graham and others 1999). These kinds of treatments can be applied to alter forest species composition and structure to meet management objectives such as producing forage for both wildlife and livestock, producing timber products, creating disease and insect resistant stands, or altering fire behavior and/or severity. Thinnings can be accomplished with hand tools, machinery, fire, or combinations of techniques. Most important, the conditions left after treatment and the subsequent forest development determines the success of thinnings in meeting forest management objectives.

Crown fires are often considered the primary threat to the ecology of the dry forest types and human values as well as the primary challenge for fire management. However, even surface and ground fires that burn fine fuels and organic layers on the forest floor can damage soils, weaken or kill overstory trees, and provide an ignition source for homes and other property (Hungerford and others 1991, Graham and others 2000, Cohen and Stratton 2003) (fig. 15, 16). Our current understanding of fire behavior in dry forests dominated by ponderosa pine and/or Douglas-fir indicates that a crown fire begins with a transition from a surface fire to the ignition of the canopy. Crown fires are therefore dependent upon the sequence of available fuels (first surface fuels-woody fuel, low vegetation and shrub strata, then ladder fuels, then canopy fuels; fig. 4, 5). Fuel management in forest stands can be designed to target specific fuel strata and disrupt the vertical progression of fire from surface fuels to ladder fuels to canopy fuels, and the horizontal progression of fire through individual fuel strata, especially from crown to crown (Scott 1998a,b, Graham and others 1999, Scott and Reinhardt 2001). Fuel treatments can increase the probability of modifying fire behavior during most weather conditions. Extreme weather conditions (low fuel moisture contents, low humidity, high winds) can create fire behavior that can burn through or breach most fuel treatments (Finney and others 2003). A realistic objective of fuel treatments is to reduce the likelihood of crown fire and other fire behavior that would lead to a loss in value or lead to undesirable future conditions, not to guarantee elimination of crown fire. Fuel treatments should integrate ecological, economic, and social values with respect to reduction of fire hazard and values at risk.

Qualitative observations, limited empirical data, and modeling provide the scientific basis for identifying how forest structure can be modified to reduce fire hazard and modify fire behavior. Additionally, research shows that when activities reduce surface fuels (low vegetation, woody fuel, shrub layer), those activities decrease the chances that surface fires will be able to ignite ladder fuels and canopy fuels (Weaver 1955, Cooper 1960, Biswell 1960, Biswell and others 1973, Martin and others 1989, Pollet and Omi 2002). The most effective strategy for reducing crown fire occurrence and severity is to (1) reduce surface fuels, (2) increase height to live crown, (3) reduce canopy bulk density, and (4) reduce continuity of the forest canopy (Van Wagner 1977, Agee 1996, Graham and others 1999, Scott and Reinhardt 2001, Cruz and others 2002). Objective, quantifiable fuel-treatment criteria will assist fire managers and silviculturists in achieving desired conditions for fuels to reduce fire hazard.

Prescribed Fire

The beneficial effects of prescribed fire on altering fuel structure and wildfire behavior and effects have long been observed and reported (Weaver 1955, 1957, Cooper 1960, Biswell and others 1973, Fernandes and Botelho 2003). There is generally less predictability in posttreatment stand structure following prescribed fire than with mechanical thinning treatments—regardless of the targeted condition and burning prescriptions, since prescribed fire is not as precise a tool for modifying stand structure and composition. While there are risks associated with use of prescribed fire because of the possibility of escapes that may cause unintended resource and economic damage, in practice, these types of problems are extremely rare relative to the large number of prescribed fires successfully conducted every year. On balance, prescribed fire is a useful tool that can effectively alter potential fire behavior by influencing multiple fuelbed characteristics, including (fig. 17):

- Reducing loading of fine fuels, duff, large woody fuels, rotten material, shrubs, and other live surface fuels, which together with compactness and continuity change the fuel energy stored on the site and potential spread rate and intensity.

Figure 17—Prescribed fire can effectively reduce surface fuels when properly applied, while maintaining high forest cover and soil productivity.

- Reducing horizontal fuel continuity (shrub, low vegetation, woody fuel strata), which disrupts growth of surface fires, limits buildup of intensity, and reduces spot fire ignition probability.
- Increasing compactness of surface fuel components, which retards combustion rates.

Prescriptions designed to remove ladder fuels will decrease the vertical continuity between surface fuels and canopy fuels. Prescribed burning often directly consumes some of the lowest ladder fuels (shrubs, dead trees, needle drape, small trees). Prescribed fire also often scorches the lower branches of the overstory trees, killing them, and effectively raising the live crown above the ground surface. Climatic and fuel moisture conditions severely restrict prescribed burning windows in many forests, especially those with high densities and heavy fuels.

Mechanical Thinning

Mechanical thinning has the ability to more precisely create targeted stand structure than does prescribed fire (van Wagtendonk 1996, Weatherspoon and Skinner 1996, Stephens 1998, Agee and others 2000, Miller and Urban 2000). Using hand-saws or machinery, specific trees can be selected for both removal and retention. Used alone, mechanical thinning, especially emphasizing the smaller trees and shrubs, can be effective in reducing the vertical fuel continuity that fosters initiation of crown fires. In addition, thinning of small material and pruning branches are more precise methods then prescribed fire for targeting ladder fuels and specific fuel components in the ladder-fuel stratum. The net effect of removing ladder fuels is that surface fires burning through treated stands are less likely to ignite the overstory canopy fuels. However, by itself mechanical thinning with machinery does little to beneficially affect surface fuels with the exception of possibly compacting, crushing, or masticating it during the thinning process. Depending on how it is accomplished, mechanical thinning may add to surface fuels (and increase surface fire intensity) unless the fine fuels that result from the thinning are removed from the stand or otherwise treated (Alexander and Yancik 1977).

Other Treatments – Mastication, Mulching, and So Forth

Additional treatments utilize machines to rearrange, compact, or otherwise change fire hazard without reducing fuel loads. In general, these treatments are limited to relatively gentle slopes and areas of high values near homes and communities. The ecological effects of these treatments vary depending on the size, composition, and location of the fuels left by these techniques (Graham and others 2000). For example, thin layers of wood chips spread on the forest floor tend to dry and rewet readily, and deep layers of both chips and chip piles may have insufficient air circulation, making poor conditions for decomposition. Moreover, when layers of small woody material are spread on the forest floor and decomposition does occur, the decomposing organisms utilize large amounts of nitrogen reducing its availability to plants. Therefore, any of these crushing, chipping, or mulching treatments need to consider their impacts on decomposition processes and their potential contribution to smoldering fires (fig. 10, 18).

Thinning and Prescribed Fire Combined

The most effective and appropriate sequence of fuel treatments depends on the amount of surface fuel present; the density of understory and mid-canopy trees; long-term potential effects of fuel treatments on vegetation, soils, and wildlife; and short-term potential effects on smoke production (Huff and others 1995). In forests that have not experienced fire for many decades, multiple fuel treatments are often required to achieve the desired fuel conditions. Thinning followed by prescribed burning reduces canopy, ladder, and surface fuels, thereby providing maximum protection from severe fires in the future (Peterson and others 2003). Potential fire intensity and/or

Figure 18—Machines can be used to chunk and chip forest residue reducing the fire hazard.

severity in thinned stands are significantly reduced only if thinnings are accompanied by reducing the surface fuels (woody fuel stratum) created from the thinning operations (Alexander and Yancik 1977, Hirsch and Pengelly 1999, Graham and others 1999). 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 (for example, mowing), to reduce crown fire hazard and the likelihood of severe ecosystem impacts from high severity fires (Peterson and others in prep).

The most appropriate fuel treatment strategy is often thinning (removing ladder fuels and decreasing tree crown density) followed by prescribed fire, piling and burning of fuels, or other mechanical treatments that reduce surface fuel amounts. This approach reduces canopy, ladder, and surface fuels, thereby reducing both the intensity and severity of potential wildfires. Mechanical treatment to manipulate fuels, used in combination with subsequent prescribed fire, offers a viable alternative, but only where mechanical treatment is feasible. For practical reasons, some areas can only be treated with prescribed fire or manual operations using chainsaws, even though the preferred prescription would involve mechanical methods as well. Restoring dry forests to a condition in which fire can be used to maintain the desired conditions will take time. Wildland fire use (that is, allowing certain wildfires to burn under certain conditions and locations) offers some hope once homes and communities and key resources are protected through thinning, prescribed fires, or other treatments.

Posttreatment Environment

Thinning and prescribed fires can modify understory microclimate that was previously buffered by overstory vegetation (Agee 1996, Weatherspoon 1996, Scott and Reinhardt 2001, Pollet and Omi 2002). Thinned stands (open tree canopies) allow incoming solar radiation to penetrate to the forest floor, which then increases surface temperatures, decreases fine fuel moisture, and decreases relative humidity compared to unthinned stands—conditions that can increase surface intensity (that is, how fast the fire is consuming fuel and producing energy) (Countryman 1955, Pollet and Omi 2002). An increase in surface fire intensity may increase the liklihood that overstory tree crowns may ignite (Van Wagner 1977). Therefore, it is important that the gap between the surface and crown fuels be maintained through either prescribed fire or pruning (fig. 9) so that if a fire should occur, the potential for crown fire initiation is minimized. Changing crown structure, while ignoring surface fuels, will only affect the likelihood of active crown fires—it will not necessarily reduce the likelihood of surface fires severe enough to damage soils or intense enough to ignite tree crowns (Alexander and Yancik 1977, van Wagtendonk 1996, Stephens 1998). Therefore, it cannot be emphasized enough that all fuel strata need to be managed (over time and space) to minimize the unwanted consequences of wildfires.

Recent estimates indicate that nearly 100 million acres of forest lands that were historically burned by frequent surface fires in the Western United States may benefit from the restoration of surface fire, and 11 million acres of forests need to be treated to protect communities from wildfire (Aplet and Wilmer 2003). In addition, Rummer and others (2003) estimate that over 66 million acres of forest lands could benefit from fuel reduction. Even with uncertainties and arguments as to the precision and accuracy of these estimates, they clearly illustrate that treatment needs for modifying fire behavior and severity are staggering. Access and operability issues further limit the options available on a large portion of Western forests, and costs and lack of industrial infrastructure to utilize small diameter material are other critical factors influencing treatment possibilities.

Treatment Longevity

There are few specific experiments that have evaluated the longevity of treatments and their effectiveness in altering fire behavior. However, there is considerable information on forest growth and development, and this information is useful in providing estimates on the longevity of potential treatments. There are good models available (Reinhardt and Crookston 2003) that predict vegetation development over time and provide estimates of treatment longevity.

There is limited information on the relation between canopy structure and ground-level vegetation, or the relation between vegetation development and fuel moisture. For short periods (months) after treatment, fuel changes can produce dramatic differences in fire behavior. Biswell and others (1973) showed that the effectiveness of prescribed fire treatments in maintaining desired fuel conditions decreased significantly over two decades in a ponderosa pine forest. Van Wagtendonk and Sydoriak (1987) directly examined fuel accumulation following prescribed burning and found that fuel amounts reached 67 percent of their preburn loading after 7 years. Many of the prescribed fires they used were the first fuel treatments that occurred in these stands in decades and would be expected to kill many small trees that would contribute to the woody fuel load. Repeated burns were not studied, but the elimination of small trees using a series of burns would be expected to retard fuel accumulation compared to the amounts they reported. Van Wagtendonk and Sydoriak (1987) concluded that prescribed burning would be required at least every 11 years to maintain fuel loads below their preburn condition. Van Wagtendonk (1995) also reported reductions in fire spread and intensity of fires up to 14 years after previous burns within the mosaic of large fires in the mixed-conifer forests of Yosemite National Park.

The duration of treatment effectiveness will vary with climate, soils, and other factors that influence productivity and the nature of the fuel treatments (Keyes and O'Hara 2002). For example, the longevity of thinning slash is greater on drier sites, particularly for finer woody material compared to fine fuels occurring in wetter forests (Christiansen and Pickford 1991). Treatment effects will likely last longer in areas in which vegetation development is slower than in areas of high productivity in which vegetation development is more rapid and lush (Weatherspoon and Skinner 1996). Few data exist, but inferences from fire history show that the length of treatment effectiveness will vary with forest type (general fuel characteristics) and fire regime (Taylor and Skinner 1998, Miller and Urban 1999, Chang 1999, Heyerdahl and others 2001, Miller 2003).

Fuel Treatment on Large Landscapes

The spatial patterns of fuel treatments in landscapes will most likely determine their effectiveness in modifying wildfire behavior (Hessburg and others 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 acres with strategically located fuel treatments (Finney 2003). Treating small or isolated stands without assessing the broader landscape will most likely be ineffective in reducing wildfire extent and severity.

The spatial arrangement of vegetation influences the growth of large fires. Patches of vegetation that burn relatively slower or less severely than surrounding patches can reduce fire intensity, severity, or spread rate, or may force the fire to move around them by flanking (at a lower intensity), which locally delays the forward progress of the fire. This modeling approach indicates that the effect of many patches dispersed throughout the landscape (conceptually placed into a herringbone pattern) containing fuels that burn slower could disrupt the forward progress of the fire and create variability in the intensity of the fire as it moves across the landscape (Brackebusch 1973, Finney 2001).

There are limited examples of how the effects of a previous fire on forest structure have altered subsequent fire behavior and severity (Helms 1979, Martin and others 1989, Pollet and Omi 2002). However, despite small-scale modification of fire behavior, none of these studies demonstrated that spread or behavior of a large fire was significantly altered, probably because the units were relatively small and were surrounded by areas containing vegetation favoring continued fire growth. In the mixed-conifer forests of northern California, fire intensity varied with dominance of short-needle or long-needle conifers in the same fire regime (frequent, low to moderately intense surface fires). Under similar burning conditions in a retrospective study of the widespread fires of 1987, stands dominated by Douglas-fir sustained significantly less damage than did stands dominated by ponderosa pine (Weatherspoon and Skinner 1995). Given current fuel accumulations across the interior West, small areas (unknown threshold) favoring low intensity or severity fires will probably be irrelevant to fire behavior (Salazar and Gonzalez-Caban 1987, Dunn 1989). Therefore, treatments that alter vegetation to favor low-intensity or less severe fires must consider spatial arrangement of fuel structures to effectively alter wildfire behavior. Large-scale, frequent mosaic burning may maintain many portions of some landscapes in a treated condition and disrupt growth of the inevitable wildfire (Brackebusch 1973). Evidence that mosaic patterns reduce fire spread comes from natural fire patterns that have fragmented fuels across landscapes. This spatial pattern produces self-limiting fire growth and behavior by management of natural ignitions, as shown in Yosemite National Park (van Wagtendonk 1995) and Sequoia National Park (Parsons and van Wagtendonk 1996).

Finney (2001) theoretically examined the importance of spatial pattern to the efficiency and effectiveness of treatment units in changing fire behavior at the landscape scale. Strategic area treatments (Finney 2001, Hirsch and others 2001) create landscape fuel patterns that collectively slow fire growth and modify behavior while minimizing the amount of treated area required. The arrangement of vegetation pattern changes fire behavior by forcing the fire to repeatedly flank around patches of treated fuels. Thus, the rate of growth of the fire is slowed, and its intensity and severity are reduced. The importance of spatial pattern is emphasized by findings that random fuel treatment arrangements (Finney 2003) are extremely inefficient in changing fire behavior (fig. 19)—requiring perhaps 50 to 60 percent of the area to be treated compared to 20 percent in a strategic fashion (Finney 2001). If fuel treatments are to be effective at changing the growth of large fires, then strategic placement of treatment areas must be capable of accommodating constraints on the amount and placement of fuel treatments because of land ownership, endangered species, riparian buffers, and other concerns. The costs and maintenance levels that would be needed to maintain this forest pattern are unknown but should vary depending on the forest type.

An alternative to a landscape approach in altering fuels is to modify portions of the vegetation in strategic locations across a landscape, and that those portions are easily accessible and can be used as fuel breaks (Weatherspoon and Skinner 1996, Agee and others 2000). The purpose of a fuel break is to reinforce an existing defensible location that can be used by firefighters to stop fire spread (Green 1977). The benefits of a fuel break are

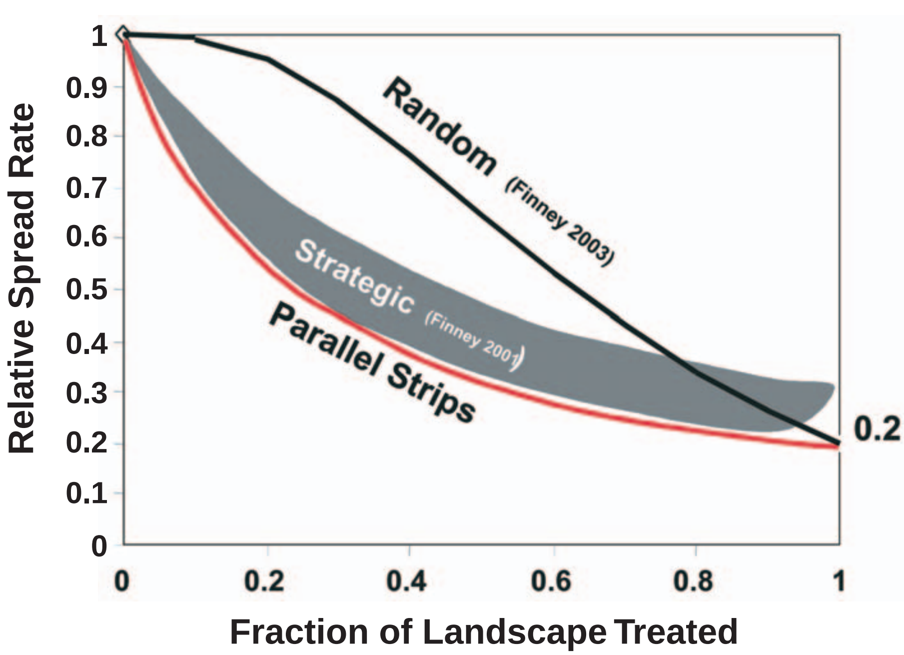

Figure 19—Comparison of large fire growth rate among different spatial fuel patterns.

only achieved if the fire suppression activities anchored to the fuel break are successful in limiting the size or perimeter of the fire. No changes in fire behavior or effects are achieved away from the fuel break or if a fuel break fails to stop fires. Moreover, fuel breaks most often require long-term maintenance and repeated treatments.

Treatment Efficacy

Fire behavior is strongly influenced by stand structure as it relates to live and dead fuel loadings and ladder fuels. The type and abundance of surface fuels, which allow falling embers to ignite and spread, also influence fire behavior. Reducing both ladder fuels and surface fuels is essential to effectively change fire behavior (fig. 20). Depending on the residual stand structure, thinning or thinning-like treatments will be less effective at reducing the risk of crown fire initiation and spread if remaining trees have crowns that reach near the ground, or if heavy surface fuel loadings remain. Conversely, reducing surface fuels and pruning lower live branches could affect fire behavior, even in fairly dense forests, by reducing the likelihood of crown ignition (Omi and Kalabokidis 1991, Graham and others 1999, Omi and Martinson 2002, Pollet and Omi 2002).

Examples from the Hayman Fire in Colorado illustrate these interactions (Finney and others 2003). The Polhemus prescribed burn in November 2001 removed most surface fuel and pruned lower live branches from trees in a

Figure 20—Forest structure (tree density, surface fuels, crown base height and so forth) can alter the intensity and severity of wildfires. The fire moving from the left to the right in this photo ceased being a crown fire as it burned into the thinned stand.

ponderosa pine forest but did not significantly reduce overstory density. These changes were sufficient to stop the Hayman Fire when it burned into the area in June 2002 even though intense fire behavior was present, facilitated by high winds (30 mph and greater) and low relative humidities (near or below 10 percent). This treatment was applied within a few months before the fire, thus decreasing the surface fuels substantially. In this case, both the time since treatment plus the treatment itself contributed to the change in fire behavior and subsequent fire severity. On the Manitou Experimental Forest (located in the Hayman Fire area), mechanical harvesting reduced density of all sizes of trees in a pure pine forest and concentrated logging slash in large piles. These actions resulted in an easily suppressed surface fire when the Hayman Fire burned into the area. On the other hand, all trees were killed in the Sheepnose Fuels Reduction Project within the Hayman Fire. Although the stand was heavily thinned from below, heavy surface fuels from nonmerchantable logging slash allowed the fire to burn intensely through this stand. It should be noted that the slash treatment was in progress at the time of the fire, and a different outcome would have been likely had the treatment been completed (Finney and others 2003).

Another example is the Cone Fire (September 2002) in northern California that burned into the Blacks Mountain Experimental Forest. The fire burned approximately 2,000 acres of a study designed to evaluate the effect varying forest structures had on wildlife. When the fire encountered forest structures in which the surface fuels had been burned and the canopy density reduced, the fire dropped from a crown to a surface fire within the first few yards of entering the treatment units. In areas where the surface fuels were not treated, the fire continued through the unit as a surface fire with variable intensity. There was considerable crown scorch and bark charring in these treatment units with areas up to 2.5 acres where all trees were dead (Skinner, personal communication).

The Biscuit Fire (August and September 2002) burned 500,000 acres, mostly in the Siskiyou National Forest, Oregon, including several areas that had been experimentally thinned 3 years earlier. Thinned stands in which the surface fuels created during thinning had not been treated experienced higher fire severity (tree mortality) than unthinned stands (C. Raymond and D. Peterson, unpublished data). A stand that had been thinned and then prescribed burned to reduce surface fuels had the lowest fire severity of all stands studied.

These examples show that it is difficult to generalize the effects of thinning forests to alter fire behavior due to variability in weather, physical setting, and forest fuels. A key point from these examples is that thinning treatments that are followed by reduction of surface fuels can significantly limit fire spread under wildfire conditions.

Evaluation Tools

Thinning (decreasing tree and/or shrub density using hand tools and/or machines) and prescribed burning are the standard tools used to reduce fuels in forests, with the most empirical data available at the forest stand scale. Treatments are typically applied at the stand scale and not across large landscapes. However, the management of fuels across large landscapes is required to effectively reduce the area and severity of fires, to increase recreation benefits, and to reduce negative effects such as smoke emissions, damage to wildlife habitat, stream habitat, and fisheries. In addition, because a small proportion of fires (approximately 1 percent) are responsible for as much as 98 percent of the fire area (Strauss and others 1989), fuel treatments need to be effective under extreme fire weather such as the weather conditions experienced during the Hayman Fire of 2002 (Bradshaw and others 2003).

Silvicultural options for fuel treatment, as summarized in Graham and others (1999) and Peterson and others (2003), provide visual displays of each thinning treatment and explain how treatments address fuel loading. Furthermore, Graham and others (1999) provide examples of how specific thinning treatments affecting stand density, height to live crown, and canopy bulk density can be linked with National Fire Danger Rating System (NFDRS) fuel models to evaluate the likelihood of crown fire following fuels treatments. Scott and Reinhardt (2001) provide the conceptual and quantitative framework for a more detailed analysis of the potential for transition from surface fire to crown fire.

The Fuelbed Characteristics Classification System (FCCS) (Sandberg and others 2001) has finer resolution than the NFDRS fuel models and is more sensitive to fuel manipulations. The FCCS estimates quantitative fuel characteristics (physical, chemical, and structural properties) and probable fire parameters from comprehensive or partial stand inventory data, and it allows users to access existing fuelbed descriptions or create custom fuelbeds for any location in the United States.

Estimating propagation of fire at broad spatial scales is more challenging but can be accomplished through geographic scaling and simulation modeling. FARSITE is the primary tool used to estimate fire spread, including crown fire, for forest landscapes (Finney 1998). This simulation approach integrates geospatial fuels data, climatic data, and fire behavior modeling (BEHAVE, Andrews 1986) to predict fire spread. Because of the analytical demands of FARSITE for data, modeling, and interpretation and its use of stylized fuel models, it is difficult to link this approach with straightforward fuel treatment guidelines. Still, FARSITE is a powerful tool for simulating the propagation of fire and comparing treatment scenarios across large landscapes, assuming that spatially explicit fuels data and good weather data are available.

The use of analysis tools can also be effective in displaying vegetation change and scheduling fuel treatments over time. For example SIMPPLE (Simulating Pattern and Process at Landscape Scales) can be used to recreate representations of historical conditions that can be compared to current conditions of specific landscapes to determine treatment priorities and treatment locations (Chew 2003). Site-specific activities can readily be evaluated using the Forest Vegetation Simulator (FVS) and the Fuel and Fire Effects extension of FVS to quantify vegetation and fuel succession following fire or fuel treatments. These evaluation tools can be used to display thinning and prescribed burning treatments such as frequent prescribed burning (say, every 5 to 20 years). This treatment sequence may be sufficient to control tree regeneration and surface fuels, but if not desirable or practical, thinning can be scheduled every 20 to 40 years, perhaps accompanied by prescribed fire. Because scheduling of fuel treatments will vary by species, elevation, aspect, climatic zone, and soil fertility, these tools can be effective in displaying the relative differences and consequences of fuel treatments.

Uncertainties in Predicting Fire Behavior

While we have a good general understanding of the factors that govern fire behavior, the interactions among these factors and the way in which fire behaves on the landscape are highly complex. As a result, fire behavior and severity can be understood and predicted in general terms, but exact predictions are not possible. Different models have been developed that are widely used and useful to assist in managing fires and developing fuel treatment plans. However, there are key uncertainties in how the simplifying assumptions of models affect their accuracy and as well as uncertainties that result from difficulties of providing adequate input data to operate the models. The limitations to predictions using models can be categorized as:

- **Model assumptions and limitations.** Because all models are abstractions of reality and not reality itself, there are many limitations to the predictions resulting from the models. By necessity, models simplify much of what really happens in order to facilitate the user's understanding of the process. In addition, many models are developed to reflect weather conditions that are "normal" and not extreme; therefore, their predictions do not reflect these types of events (Albini 1976, Van Wagner 1977, Rothermel 1983, Andrews 1986).
- **Unknowable fire environment at the time wildfires encounter treatments.** Even if models were nearly perfect, we would never be able to predict the exact conditions of a wildfire that would encounter a fuel treatment and serve as the performance measure. For example, the weather and wind conditions at a particular time, the attendant ignition location and direction of fire movement through the treatment, the degree of variability in the treatment conditions at the time of the fire—all these determine the performance of a fuel treatment in terms of the changes to fire behavior and effects.
- **Coarse data descriptions of fuels and environmental conditions.** The most detailed fuel maps are typically resolved to about 30 m, but this scale is still too coarse to reflect variability within that area, such as heavy fuel concentrations or thickets of trees. Such fine-scale variability could be important and may have important consequences to fire growth over landscapes, but it is unknowable for fire modeling. Our fuel data today tend to smooth out variation in order to represent the "average" condition. However, the average fuel condition does not produce the average fire behavior response because fire behavior responds nonlinearly to changes in fuels and weather.

A key area of uncertainty is in how to determine thresholds of treatment for different fuels when they are encountered by wildfire. Even though models cannot predict how a given structure created by a fuel treatment will fare when a wildfire encounters it, they can predict a range of conditions under which fuel conditions will modify fire behavior and/or severity. In general, models are effective in showing the contributions to the fire hazard made by the different fuel strata—that is, the surface fuels, ladder fuels, and crown fuels. However, each stratum affects fire behavior differently, and there is uncertainty about how much treatment is needed in each stratum to achieve desired results.

Stand structure and wildfire behavior are clearly linked (Weaver 1943, 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. However, a majority of the evidence supporting the effectiveness of fuel treatments for reducing crown fire hazard is based on informal observations, nonsystematic inquiry, and simulation modeling (Omi and Kalabokidis 1991, Scott 1998a,b, Stephens 1998, Finney 2001). However, there are currently ongoing studies (not yet published) that are adding to our limited empirical knowledge on the relation between forest structure and fire behavior (Jain and others 2001, Pollet and Omi 2002, Omi and Martinson 2002, Fire and Fire Surrogate studies, http://ffs.psw.fs.fed.us).

Summary

In many temperate ecosystems, especially the dry forests of the interior West, biomass accumulates faster than it decomposes. Fire is the ecological force that restores this balance. The decrease in fire occurrence in many of these systems has disrupted the process, adding to available fuel and changing forest structure. These changes increase the risk of uncharacteristically severe surface fires and of initiating and sustaining crown fires. For some ecosystems, such as those dominated by ponderosa pine and Douglas-fir, crown fires are a historical anomaly that affects a range of ecological conditions and socioeconomic values. Although homes in the path of a wildfire are perhaps the most immediately recognized value at risk, severe wildfires put numerous other important values at risk including: critical infrastructure, critical fish and wildlife habitat, firefighter and public health and safety, soil productivity, clean air, and functional fire-adapted ecosystems. Some of these values are also threatened by the secondary effects of wildfire, such as landslides, soil erosion, and the spread of exotic species. This risk can be reduced in some cases by management efforts to alter forest structure and decrease fuel loads.

Forest ecosystems are inherently complex entities about which we have limited 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 altering fuels and fire hazard. In the face of this complexity, it is important to focus on basic principles that assist decisionmaking processes (table 1) (Agee 2002b, Peterson and others 2003).

Table 1—Principles of fire-resilient forests (adapted from Agee 2002b).

Objective	Effect	Advantage	Comments
Reduce surface and ladder 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 ignite tree crowns	Less torching	Opens understory, may allow surface wind to increase
Decrease crown density	Makes independent crown fire less probable	Reduces crown fire propagation	Surface wind may increase, surface fuels may be drier
Increase proportion of fire-resistant tree species	Thicker bark, taller crowns, higher canopy base height	Increases survivability of trees	Removing smaller trees is sometimes problematic

As empirical data on fuel treatments and wildfires improve, we anticipate that more informed decisions can be made for altering forest structure and composition to impact wildfire behavior and severity in dry forests of the interior West. Appealing as the idea may be, there is no "one size fits all" solution. Given that fire behavior and resulting severity result from the combination of weather, available fuels, and physical setting, the design of site-specific solutions will be highly variable. Although there continues to be a need for further work to understand fire behavior, a long-standing and large body of knowledge about the role of forest structure and fuels on fire behavior and severity provides a sound foundation for managers to develop prescriptions for hazard reduction and restoration of dry conifer forests at the stand level (for example, within individual treatment units). Fuel management intended to mitigate the effects and behavior of large fires, however, requires a landscape level perspective, encompassing many forest types, stands, treatment units, prescriptions, and their spatial arrangement. Current research clearly indicates the potential of fuel treatments to reduce large fire growth, thereby reducing the chances of fires leaving wildland areas, but only if the spatial arrangement of the treatment units is considered and planned for.

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