The Interaction of Fire, Fuels, and Climate across Rocky Mountain Forests

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Understanding the relative influence of fuels and climate on wildfires across the Rocky Mountains is necessary to predict how fires may respond to a changing climate and to define effective fuel management approaches to controlling wildfire in this increasingly populated region. The idea that decades of fire suppression have promoted unnatural fuel accumulation and subsequent unprecedentedly large, severe wildfires across western forests has been developed primarily from studies of dry ponderosa pine forests. However, this model is being applied uncritically across Rocky Mountain forests (e.g., in the Healthy Forests Restoration Act). We synthesize current research and summarize lessons learned from recent large wildfires (the Yellowstone, Rodeo-Chediski, and Hayman fires), which represent case studies of the potential effectiveness of fuel reduction across a range of major forest types. A "one size fits all" approach to reducing wildfire hazards in the Rocky Mountain region is unlikely to be effective and may produce collateral damage in some places.

Keywords: fire ecology, forest management, forest health, Rocky Mountain forests, climate

The interaction between climate, fuels, and the frequency and severity of wildfires across Rocky Mountain forests is complex. A comprehensive understanding of the relative influence of fuels and climate on wildfires across this heterogeneous region is necessary to predict how fires may respond to a changing climate (Dale et al. 2001) and to define effective fuel management for controlling wildfires in this increasingly populated region (USDA 2002). The annual area burned by wildfires has apparently increased during the last few decades across North America, and in the southern Rocky Mountain region in particular, possibly in response to recent climate change and the gradual accumulation of fuels following decades of effective fire suppression (figure 1; Grissino-Mayer and Swetnam 2000). However, more complete modern records, and an increase in land under federal protection since the 1960s, may also have contributed to this apparent trend over the last half-century. Nonetheless, the United States recently experienced a series of big fire years: According to the National Interagency Fire Center (*www.nifc.gov*), wildfires in 1988, 2000, and 2002 burned 3.0 million, 3.4 million, and 2.8 million hectares (ha), respectively, Most of these fires took place in the western United States, which is characterized by fire-prone ecosystems.

In an effort to mitigate the risk to life and property from wildfires and the high cost of fighting fire throughout the western United States, fuel reduction has become an important forest and fire management tool. In 2002, thinning and prescribed-fire projects were carried out across 1 million ha of federal land as part of the US National Fire Plan (*www.fireplan.gov*) to reduce the fire hazard and to restore historical species composition and stand structures. The goals of fire-hazard reduction and ecological restoration may converge in some ecosystems, yet they may be incompatible in others (Veblen 2003).

The idea that decades of fire suppression have promoted unnatural fuel accumulation and subsequent unprecedentedly large, severe wildfires across western forests was developed primarily from experience in dry ponderosa pine (*Pinus ponderosa*) forests in the US Southwest, the interior West, and the Sierra Nevada (Covington and Moore 1994, Caprio and Swetnam 1995, Moore et al. 1999). Historically, short-interval, low-severity surface fires maintained sparse, open stands in most dry ponderosa pine forests (Swetnam and

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Baisan 1996). With fire suppression, young fire-intolerant trees can establish during lengthened fire intervals. Denser stands provide "ladder" fuels at intermediate heights that carry fire up into continuous canopy fuels, promoting unprecedentedly large, catastrophic fires. This system has presented a strong case for thinning to reduce the fire hazard and to restore historical stand structure.

Ecological restoration and fire mitigation are urgently needed in dry ponderosa pine forests, where previous research supports this management action. However, we are concerned that the model of historical fire effects and 20th-century fire suppression in dry ponderosa pine forests is being applied uncritically across all Rocky Mountain forests, including places where it is inappropriate (e.g., USDA 2002, White House 2002). Of particular concern is President Bush's Healthy Forests Initiative, which identifies unnatural fuel buildup as a widespread risk across the West: "Today, the forests and rangelands of the West have become unnaturally dense, and ecosystem health has suffered significantly. When coupled with seasonal droughts, these unhealthy forests, overloaded with fuels, are vulnerable to unnaturally severe wildfires. Currently, 190 million acres [77 million ha] of public land are at increased risk of catastrophic wildfires" (White House 2002, executive summary). This initiative was recently enacted as HR 1904, the Healthy Forests Restoration Act of 2003.

The relative contribution of fuels and climate to recent fire activity across forest types throughout the western United States is hotly debated (e.g., see *Conservation Biology,* vol. 15 [2001]). It is easy to identify either local situations in which fire suppression has allowed unusual fuel accumulations or, by contrast, those in which fuel conditions remain within the historical range and the effects and frequency of fire are controlled primarily by weather conditions, not by fuels. What is lacking is a broad synthesis of the geographical patterns in historical fire regimes, and of 20th-century changes in these regimes, addressing these key questions:

- Where, in what ecosystem types, and to what degree have fuels increased with fire suppression across the Rocky Mountain region (Arizona, New Mexico, Colorado, Utah, Wyoming, Montana, and Idaho)?
- Where are forest restoration treatments appropriate, and how will fire respond to fuel-reduction treatments in different forest types?
- Where and when is the influence of short-term (i.e., seasonal and annual) climatic variation expected to override the effectiveness of fuel treatments?

To address these questions, we synthesize current understanding of the different types of fire regimes (defined by the historical range of variability in fire size, severity, and frequency) that occur across the Rocky Mountain region. The fire regime is a central concept in fire ecology and is essential for understanding the character, effect, and variability of disturbance patterns across regions. Our analysis of different fire regimes is based on the classic fire triangle of weather, fuels, and ignition, which identifies the factors controlling combustion. All three factors must be present in a form conducive to

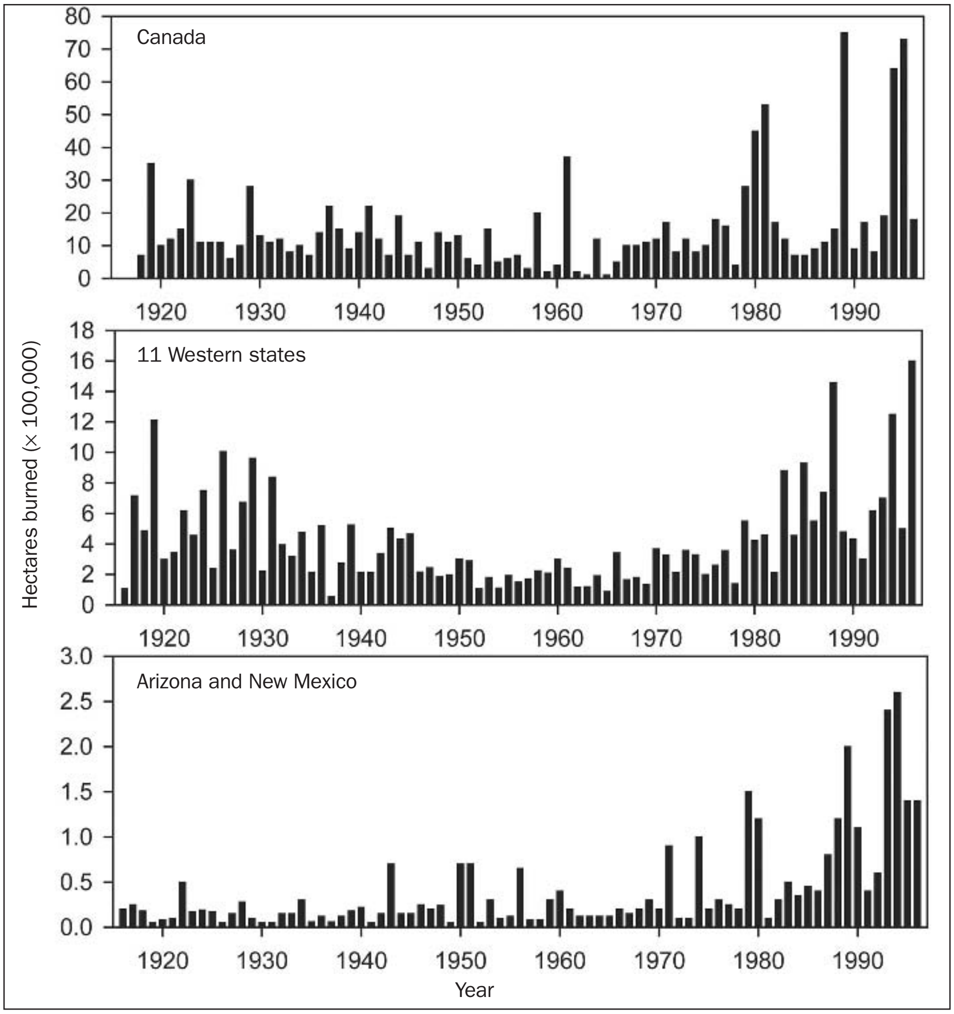

Figure 1. Area burned by wildfires in different regions under federal protection across North America. The apparent increase in the extent of fires over the last century is most pronounced in the southwestern United States (Arizona and New Mexico), although we urge caution in interpreting these trends. Source: Grissino-Mayer and Swetnam (2000); reprinted with permission from **The Holocene.**

combustion, or fire will not occur. However, the inherent variability, and therefore the limiting role, of these three ingredients is dramatically different among forest types and geographic regions. For example, we argue below that fuel types and amounts are less limiting to fire spread in subalpine forests than in low-elevation forests, but suitably dry weather conditions for fire spread in subalpine forests occur infrequently. Hence, variability in seasonal and annual climate is more limiting and has a greater influence on fire extent and severity in these generally cool, moist ecosystems.

In contrast, periods of several months of warm, dry weather occur almost annually in most southwestern ponderosa pine forests, leaving fuels sufficiently desiccated for extensive fires to occur annually. Given the higher frequency of weather conditions that desiccate fuels in this ecosystem, factors that affect fuel type, quantity, and configuration are more limiting than climate in controlling this fire regime. Variations in local site productivity, and in the time elapsed since the last fire event, affect fuel accumulation in the dry, low-elevation ponderosa pine forests. Annual climatic variation affects fuels indirectly in these forests both through short periods of above-average moisture availability, which enhance the production of fine fuels (e.g., leaves, grasses, forest litter), and through fuel-desiccating drought. But overall, climate is more limiting in subalpine forests, where short-term (i.e., months to a few years) variability in climate primarily affects fire severity and spread through fuel desiccation and wind, not fuel abundance. In contrast, the fire regime in dry ponderosa pine woodlands is more limited by annual variability in fine fuel amounts and by ladder-fuels related to the time elapsed since the last fire. Ignition sources also may be important, at least locally, but in this study we do not identify spatial patterns in this component of the fire regime. Assuming instead that ignition sources are always available, we evaluate the relative importance of variability in short-term climatic variation and in fuel quantity and configuration.

We identify three major types of historical fire regimes (Agee 1998): (1) high severity, (2) low severity, and (3) mixed severity. In addition to developing a general theoretical framework for assessing controls on local fire regimes, we summarize the lessons learned from three recent large wildfires (the 1988 Yellowstone fires and the 2002 Rodeo-Chediski and Hayman fires). These case studies reveal the potential effectiveness of fuel reduction under varying climate conditions across a range of major forest types and historical fire regimes. Finally, we develop coarse estimates of the spatial extent of the three major historical fire regimes to broadly quantify heterogeneity in fire regimes and responses to fire suppression across the Rocky Mountain region.

To develop coarse estimates of the proportion and extent of historical fire regimes across the Rockies, we rely on research reported in the peer-reviewed literature to group major forest types that historically experienced each of the three major fire regimes we discuss. Because it is relatively difficult to define the spatial extents of different fire regimes at this scale, we rely on two independent maps of forest cover to highlight general trends and degrees of uncertainty in the relative proportion of major fire types across the Rocky Mountain region. In the first analysis, forest types are based on a map of Küchler's potential natural vegetation (PNV) groups (climax vegetation types that are expected, given the occurrence of natural disturbances such as fire, based on site characteristics such as soils, climate, and topography), modified by Schmidt and colleagues (2002). In our reclassification of these data, we combine eight PNV groups into three main forest types: (1) ponderosa pine (pine forest and Great Basin pine), (2) mixed ponderosa pine (pine–Douglas fir, Douglas fir, grand fir–Douglas fir, and Southwest mixed conifer [Arizona, New Mexico]), and (3) spruce–fir (spruce–fir and spruce–fir–Douglas fir). In the second analysis, forest types are based on a map of current cover types, which Schmidt and colleagues (2002) developed by combining the Forest and Range Resource Planning Act map of US forest type groups with AVHRR (Advanced Very High Resolution Radiometer) satellite imagery. In our reclassification of these data, we combine the current cover types into three main forest types, similar to those obtained by combining the PNV groups: (1) ponderosa pine, (2) Douglas fir, and (3) spruce–fir–lodgepole pine.

In this summary, we assume a one-to-one correspondence between forest types and fire regimes; however, as we emphasize throughout the text, this is a considerable oversimplification. Nonetheless, this summary reveals coarse levels of heterogeneity in fire regimes across the Rocky Mountain region, unaccounted for in current forest policy debates. Other endeavors to define fire regimes at this scale include the work of Schmidt and colleagues (2002), who developed a map of historical fire regimes and departures from historical conditions throughout the continental United States for strategic fire-planning purposes, but who relied primarily on managers' expert knowledge rather than on peer-reviewed empirical studies in defining fire regimes. In addition, McKenzie and colleagues (2000) developed a regional model of fire frequency within the interior Columbia River basin, based on a large fire-history database from the western United States.

Overall, our analysis highlights the heterogeneity of forest types and fire regimes across the Rocky Mountain region. Further, it provides insight into pressing management questions of when and where various fuel treatments are consistent with the goal of ecological restoration, and where such treatments are likely to be successful in reducing the size and severity of wildfires. We focus on the Rocky Mountain region; however, the spatial and geographic heterogeneity in fire regimes across this region is also evident throughout the West (e.g., Agee 1998).

High-severity fire regimes

High-severity or stand-replacing fires are defined by the death of canopy trees, in contrast to low-severity fires, which do not kill overstory trees. High-severity fires typically burn the treetops (crown fires) but may also kill trees through very hot surface fires, which primarily burn the forest floor.

High-elevation subalpine forests in the Rocky Mountains typify ecosystems that experience infrequent, high-severity crown fires (Peet 2000, Veblen 2000). The forest types that occur in the subalpine zone range from mesic spruce–fir forests to drier, dense lodgepole pine stands; and xeric, open woodlands of limber and bristlecone pine. The most extensive subalpine forest types are composed of Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and lodgepole pine (*Pinus contorta*), all thin-barked trees easily killed by fire.

Extensive stand-replacing fires occurred historically at long intervals (i.e., one to many centuries) in subalpine forests (Romme 1982, Kipfmueller and Baker 2000, Veblen 2000, Schoennagel et al. 2003), typically in association with infrequent high-pressure blocking systems that promote extremely dry regional climate patterns (Romme and Despain 1989, Renkin and Despain 1992, Bessie and Johnson 1995, Nash and Johnson 1996). Persistent high-pressure blocking systems affect regional temperature and precipitation patterns throughout the Rockies and may respond to global climate anomalies (Baker 2003). Regional synchrony of large, high-severity fires across subalpine forests corroborates the idea that high-elevation forest fires respond to broad scale synoptic climate (Nash and Johnson 1996, Kipfmueller and Baker 2000, Veblen 2000, Baker 2003). In moist high-elevation forests, successive seasons of drought can initiate large, stand-replacing fires (Balling et al. 1992, Kipfmueller and Swetnam 2000). In these generally cool subalpine environments, significant drought events are infrequent, which prevents the frequent occurrence of large, high-severity fires. Although they occur infrequently, drought-induced large fire events account for the greatest percentage of the area burned in subalpine forests (figure 2; Bessie and Johnson 1995).

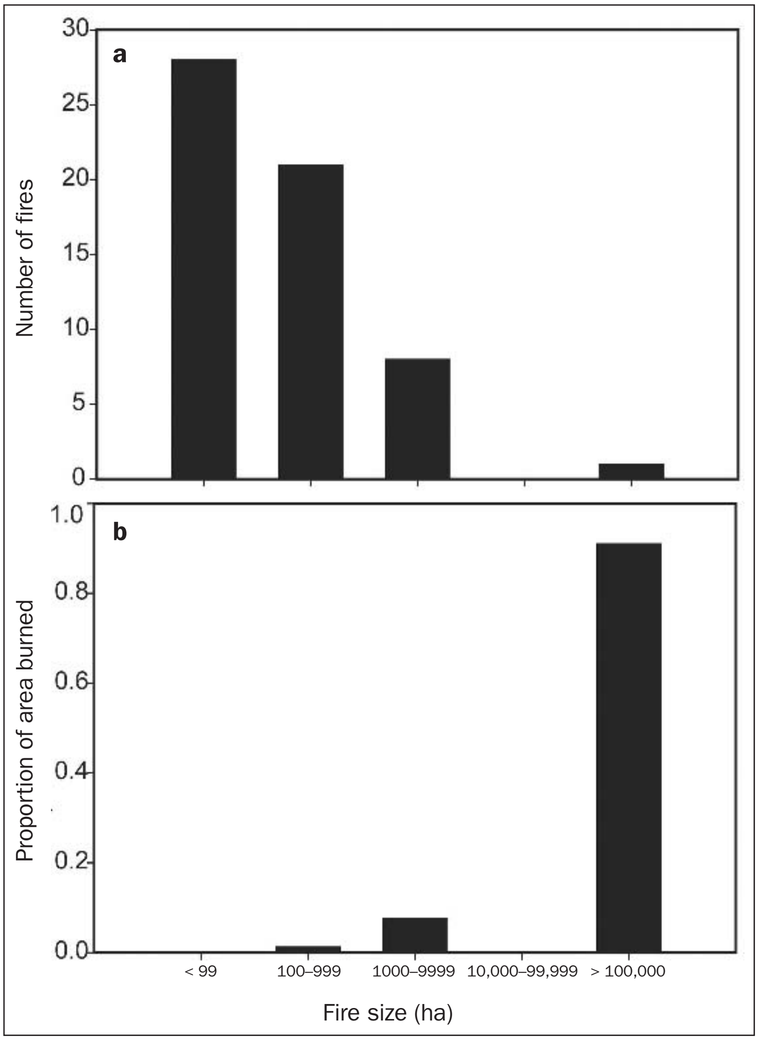

Figure 2. (a) Histogram of the occurrence of different size classes of stand-replacing fires in Yellowstone National Park (1895–1991). (b) Proportion of the total area burned in each size class for the same period (1.0 = 100% of total area). Although large stand-replacing fires (i.e., fires that burn more than 1000 hectares) are infrequent, they are the dominant influence on subalpine forests. Data are from Balling and colleagues (1992).

Subalpine forests typically experience stand-replacing crown fires, rather than low-severity surface fires, because they lack fine fuels on the forest floor but have abundant ladder fuels that carry fire into the treetops. These dense, closed-canopy forests typically support sparse understory vegetation, and the short, stout needles of subalpine trees compact tightly on the forest floor, creating a poor substrate for fire spread (Swetnam and Baisan 1996). This is in stark contrast to the warmer, open-canopied, productive forests at lower elevations, which support abundant, well-aerated fine fuels on the forest floor (Swetnam and Baisan 1996). Although fine surface fuels are sparse in subalpine forests, ladder fuels are abundant. Shade-tolerant fir and spruce trees have abundant lateral branches, which easily carry fire up into the canopy. By contrast, shade-intolerant lodgepole pines have few lateral branches, but these trees tend to grow in very dense stands that thin over time, contributing to abundant dead ladder fuels (figure 3). The abundance of ladder fuels, the proximity of crowns, and the lack of abundant, spatially continuous fine surface fuels all promote high-severity crown fires that dominate subalpine forests.

The low abundance of small fuels, and the relatively high abundance of large dead and live fuels, explains why fires are infrequent but typically large in subalpine forests. Fuel moisture levels respond to ambient environmental conditions and are critical in determining fire potential. Small-diameter dead fuels dry quickly; for example, 1-hour fuels (particles less than 0.6 centimeters [cm] in diameter) approach equilibrium with ambient relative humidity within an hour. By contrast, dead branches, logs, or other large, slow-drying materials (7.6 to 20.3 cm in diameter) are known as 1000-hour fuels because they require 1000 hours to equilibrate (figure 4). Live fuels dry even more slowly than dead fuels and are influenced most strongly by sustained periods of drought. Because of the paucity of small dead fuels such as needles and grasses in subalpine forests, short-duration drying episodes generally do not create sufficiently dry conditions to sustain a fire. However, prolonged dry weather conditions (about 40 days without precipitation) can sufficiently dry live fuels and larger dead fuels to carry large, intense fires once they are ignited (figure 5). Conditions necessary for large fires are infrequent and often coupled with the occurrence of lightning. This suggests that Native Americans probably did not have a major influence on fires in the subalpine forest types, except in some localized areas.

The recent period of consistent, effective fire suppression in remote high-elevation sites, which has lasted 50 years at most, represents only a small portion of typical fire-free intervals in subalpine forests. Studies of fire history show that long fire-free periods (as long as, or longer than, the fire exclusion period during the 20th century) characterized the fire regimes of these forests before Euro-American settlement (Romme 1982, Romme and Despain 1989, Kipfmueller and Baker 2000, Veblen 2000, Schoennagel et al. 2003). Therefore, it is unlikely that the short period of fire exclusion has significantly altered the long fire intervals in subalpine forests (Romme and Despain 1989, Johnson et al. 2001, Veblen 2003). Furthermore, large, intense fires burning under dry conditions are very difficult, if not impossible, to suppress (Wakimoto 1989), and such fires account for the majority of area burned in subalpine forests (figure 2; Romme and Despain 1989, Bessie and Johnson 1995). At lower elevations within its range, lodgepole pine may also experience occasional small surface fires (Kipfmueller and Baker 2000), but their spatial extent and frequency are not well quantified. Suppression of smaller, less intense fires under moderate climate conditions probably has had little influence on the dominant fire regime in subalpine forests (Johnson et al. 2001, Veblen 2003). Our understanding of the dominant fire regime in these high-elevation, cool forests leads us to conclude that any recent increases in area burned in subalpine forests are probably not attributable to fire suppression. Evidence from the subalpine forests of Yellowstone indicates that fires of comparable size to the 1988 fires occurred in the early 1700s (Romme and Despain 1989).

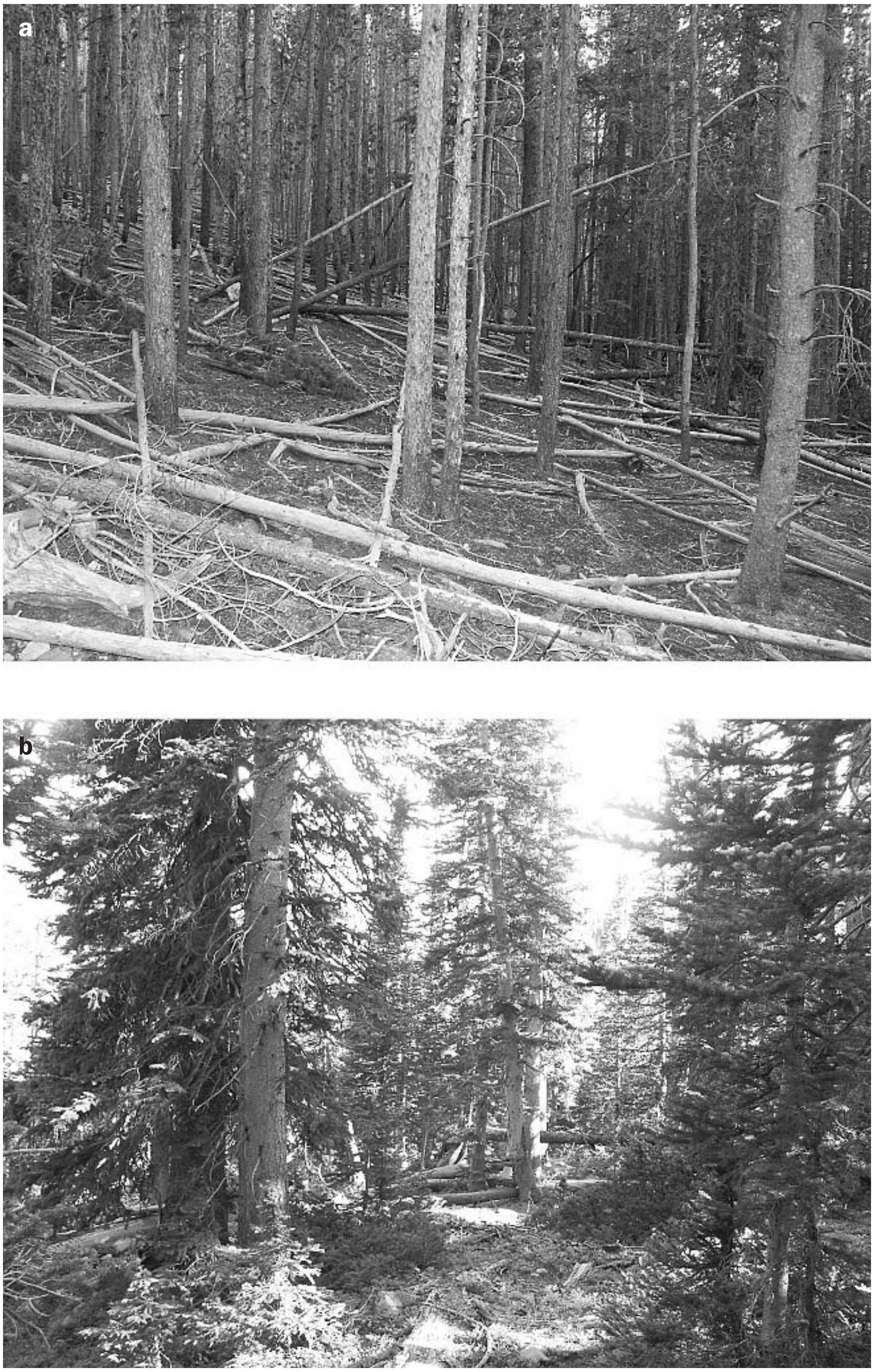

Figure 3. Typical subalpine forest stand structure, which easily carries fire into the canopy, promoting high-severity crown fires. (a) Lodgepole pine stand with sparse understory fuels and high tree densities. (b) Spruce–fir stand with abundant live ladder fuels throughout the vertical profile. Photographs: Tania Schoennagel.

Moreover, there is no consistent relationship between time elapsed since the last fire and fuel abundance in subalpine forests (Brown and Bevins 1986), further undermining the idea that years of fire suppression have caused unnatural fuel buildup in this forest zone. For example, lodgepole pine stands experience high rates of self-thinning that contribute large dead fuels as stands mature (Kashian 2003). However,

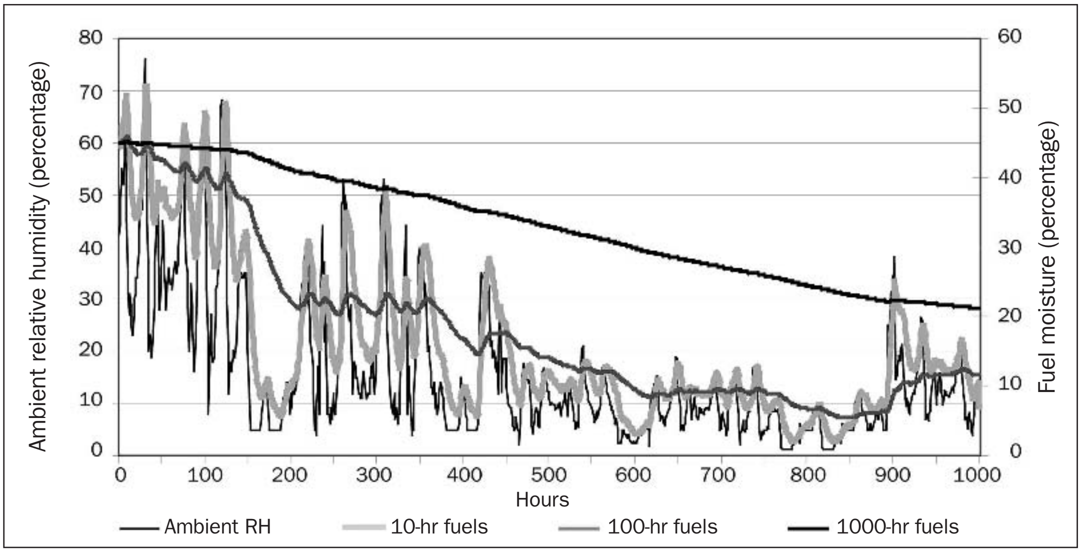

Figure 4. A theoretical example illustrating differences in fuel-moisture time lags for small (10-hour), intermediate (100-hour), and large (1000-hour) fuels. Small fuels dry out rapidly and respond more quickly to short-term variability in ambient relative humidity, while large fuels exhibit a more lagged response, requiring much longer dry periods to reach similar dryness.

the legacy of wood from the prefire stand contributes abundant loads of large fuel to young postfire stands (Romme 1982). Bessie and Johnson (1995) report little variation in total fuel loads, relative to variation in weather, in subalpine forests of different ages. No evidence suggests that spruce–fir or lodgepole pine forests have experienced substantial shifts in stand structure over recent decades as a result of fire suppression. Overall, variation in climate rather than in fuels appears to exert the largest influence on the size, timing, and severity of fires in subalpine forests (Romme and Despain 1989, Bessie and Johnson 1995, Nash and Johnson 1996, Rollins et al. 2002). We conclude that large, infrequent stand-replacing fires are "business as usual" in this forest type, not an artifact of fire suppression.

Case study: The 1988 Yellowstone fires. In 1988, according to the National Interagency Fire Center, more than 700,000 ha burned in mostly high-elevation subalpine forests throughout Wyoming, Montana, and Idaho. Yellowstone National Park was the focus of public attention during these fires. Some 40% of the park burned, much of it at high severity (Turner et al. 1994). Drought, which had started years earlier, extended beyond its immediate region during the summer of 1988. From 1977 to 1989, a strong Pacific North America pattern developed, creating a blocking ridge over the northwestern United States that reduced winter snowpack across Montana and Wyoming (Baker 2003). Low winter snowpack in 1988, followed by an unusually dry, hot, and windy summer, contributed to extreme burning conditions in the park (Balling et al. 1992). Precipitation in July and August was only 20% of normal levels; relative humidity fell to 6%; and strong, dry, gusty winds (60 to100 kilometers [km] per hour) spread multiple fires ignited by humans and lightning.

Variation in daily area burned was highly correlated with the moisture content of 100-hour (2.5- to 7.6-cm diameter) and 1000-hour dead fuels (Turner et al. 1994). Once fuels reached critical moisture levels later in the season, the spatial pattern of the large, severe stand-replacing fires was controlled by weather (wind direction and velocity), not by fuels, stand age, or fire-fighting activities (Minshall et al. 1989, Wakimoto 1989, Turner et al. 1994). Variation in fuel abundance and topography (including formidable barriers such as the Grand Canyon) had little influence on the severity or direction of the fire when fuel moistures were critically low (Turner et al. 1994). Stand-replacing fire affected stands of all ages, including some as young as 7 years old (Schoennagel et al. 2003).

Contrary to popular opinion, previous fire suppression, which was consistently effective from about 1950 through 1972, had only a minimal effect on the large fire event in 1988 (Turner et al. 1994). Reconstruction of historical fires indicates that similar large, high-severity fires also occurred in the early 1700s (Romme and Despain 1989). Given the historical range of variability of fire regimes in high-elevation subalpine forests, fire behavior in Yellowstone during 1988, although severe, was neither unusual nor surprising.

Summary: High-severity fire regimes in subalpine forests. Subalpine forests that experience infrequent, high-severity fires cover approximately 32% to 46% of the forested area in the Rocky Mountain region, which encompasses the three major forest types discussed in this article (table 1). The following insights are drawn from analyses of historical fire regimes and contemporary fire behavior in subalpine forests.

- Infrequent, high-severity, stand-replacing fires dominate the historical and contemporary fire regime in these forests.
- Climatic variation, through its effects on the moisture content of live fuels and larger dead fuels, is the predominant influence on fire frequency and severity.
- Dense trees and abundant ladder fuels are natural in subalpine forests and do not represent abnormal fuel accumulations.

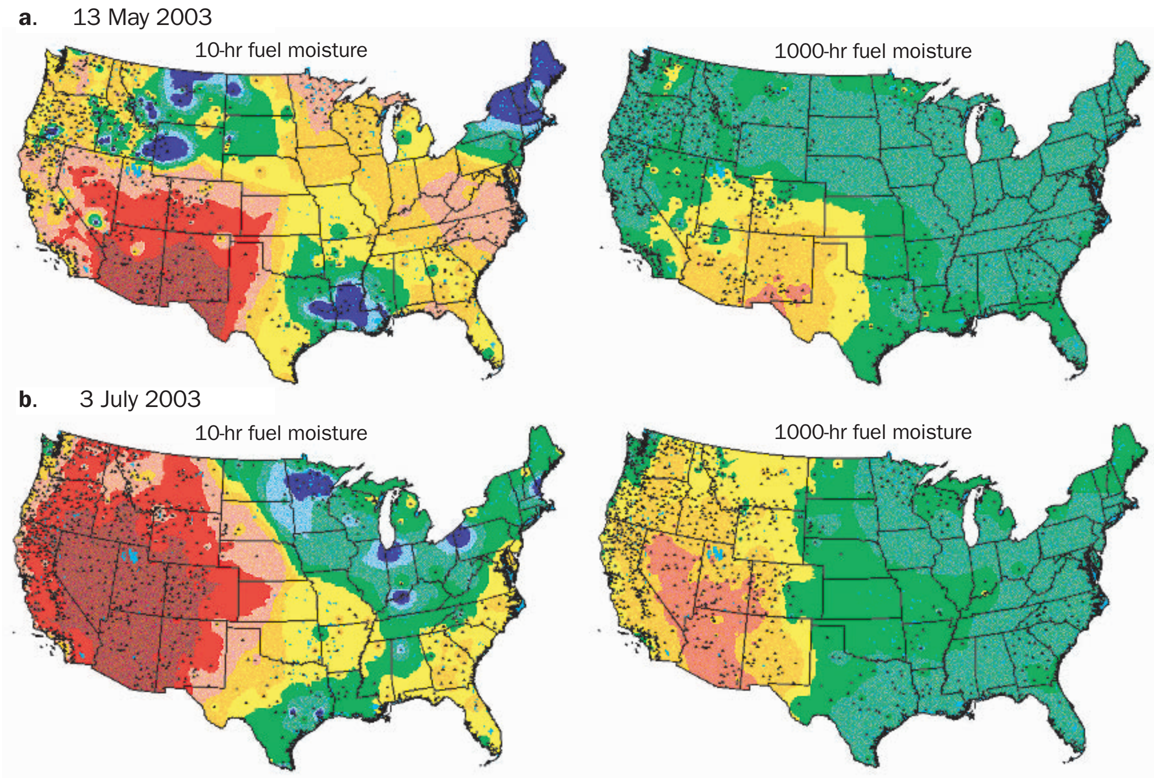

Figure 5. Maps of fuel moisture for small (10-hour) and large (1000-hour) fuels, showing responses to (a) short-term (1- to 2-day) and (b) longer-term (1- to 2-month) drying conditions in the southwestern United States. Large fuels dry sufficiently to carry fire only under longer drying conditions, while smaller fuels may dry sufficiently to carry fire under short-term or moderate drying conditions. The maps were developed by the National Interagency Fire Center (17 June 2004; www.fs.fed.us/land/wfas/wfas10.html).

- Fire suppression has had minimal influence on the size, severity, and frequency of high-elevation fires.
- Mechanical fuel reduction in subalpine forests would not represent a restoration treatment but rather a departure from the natural range of variability in stand structure.
- Given the behavior of fire in Yellowstone in 1988, fuel reduction projects probably will not substantially reduce the frequency, size, or severity of wildfires under extreme weather conditions.

Low-severity fire regimes

In marked contrast to the infrequent, high-severity fire regimes characteristic of subalpine forests, many low-elevation ponderosa pine forests historically experienced frequent, low-severity fires. A meta-analysis of 63 fire histories from similar-size southwestern ponderosa pine sites (10 to 100 ha) indicates that surface fires returned at mean intervals of 4 to 36 years (based on fire dates recorded for more than 10% of the sampled trees; Swetnam and Baisan 1996), an order of magnitude shorter than the intervals for subalpine forest stands. Some low-elevation ponderosa pine stands in Colorado, near the Plains grasslands, show evidence of 8- to 10-year intervals for fire returning to the same small stand or tree before the 1900s (Veblen et al. 2000). In the Black Hills of South Dakota, the mean fire interval was 20 to 23 years at each of four low-elevation ponderosa pine sites (about 100 ha each) for the period from 1388 to 1900 (Brown and Sieg 1996). Although detailed comparison of fire-interval statistics across study sites is problematic because of differences in the extent of the study area and the intensity of sampling, these studies clearly indicate a significant difference in fire interval and severity between low-elevation, dry ponderosa pine forests and high-elevation, moist subalpine forests.

Frequent, low-severity fire regimes occurred predominantly in dry, low-elevation ponderosa pine forests that were formerly open woodlands with abundant, contiguous fine fuels in the understory. This surface fuel layer, dominated by grasses and long cast needles, dries easily and thus promotes the spread of frequent surface fires. Historically, climate, fine-fuel abundance, and fire were highly interrelated in dry, low-elevation ponderosa pine forests. El Niño–Southern Oscillation (ENSO) patterns correlate tightly with the incidence of synchronous, low-severity fires in dry, low-elevation forests of the Southwest (Swetnam and Baisan 1996, Grissino-Mayer and Swetnam 2000, Kitzberger et al. 2001). The ENSO cycle alternates between El Niño and La Niña conditions at

Table 1. Two coarse estimates of the extent and proportion of three major forest types across the Rocky Mountain region (Arizona, New Mexico, Colorado, Utah, Wyoming, Montana, and Idaho). The first estimate is based on a map of Küchler's potential natural vegetation groups, modified by Schmidt and colleagues (2002). The second estimate is based on a map of current cover type developed by Schmidt and colleagues (2002). A different historical fire regime is associated with each of the three forest types, although the correspondence is not exact.

Forest type	Area (hectares)	Percentage of total	Associated severity of historical fire regime
Based on PNV groups			
Ponderosa pine (pine forest, Great Basin pine)	8,201,600	17.7	Low
Mixed ponderosa pine (pine–Douglas fir, Douglas fir, grand fir–Douglas fir, Southwest mixed conifer)	23,176,200	49.9	Mixed
Spruce–fir (spruce–fir, spruce–fir–Douglas fir)	15,056,000	32.4	High
Total	46,433,800	100.0	
Based on current cover types			
Ponderosa pine	13,009,100	36.7	Low
Douglas fir	6,176,000	17.4	Mixed
Spruce–fir–lodgepole pine (lodgepole pine, fir–spruce)	16,287,200	45.9	High
Total	35,472,300	100.0	

PNV, potential natural vegetation.

Note: Total is the forested area in the Rocky Mountain region defined by the three major forest types listed. Some other forest types, such as piñon-juniper woodlands, are not included.

2- to 6-year frequencies. In the southern Rockies, El Niño years are characterized by wetter-than-average winter and spring conditions, which enhance the growth of fine fuels (especially grasses). Drier-than-average La Niña years typically follow, desiccating abundant fine surface fuels. Time-lag analysis shows that dry, low-elevation ponderosa pine forests commonly experience more extensive fires when wetter conditions 1 to 3 years before a fire are followed by dry conditions during the year of the fire. Infrequent or anomalous prolonged drought conditions are not the primary factor promoting fires in dry, low-elevation pine forests, as they are in subalpine forests. Summers in the low-elevation forests are typically dry enough to promote low fuel moisture levels that would permit ignition, although the abundance and continuity of fine surface fuel historically were the primary limiting factors (Swetnam and Baisan 1996, Rollins et al. 2002).

Unlike the historical fire regime in subalpine forests, the fire regime in dry, low-elevation ponderosa pine forests has been significantly altered as a result of fire suppression and its effects on historical fuel structure (Arno and Gruell 1983, Swetnam and Baisan 1996, Veblen et al. 2000). Before fire suppression, the frequent, low-severity surface fires in these forests kept dry ponderosa pine stands sparse and open by killing young, newly established trees. With fire suppression and livestock grazing (which reduces the amount of grass fuel), fire intervals have lengthened, and dense stands have developed in which fine grass fuels are less abundant and dense ladder fuels are capable of carrying fire up into the canopy (figure 6). Consequently, high-severity fires potentially can occur in dry ponderosa pine forests, where historically they were rare because of the sparse ladder fuels and the lack of contiguous tree crowns. This pattern has been well documented on the basis of fire scars, repeat photography, and stand age structures, especially for forests in Arizona and New Mexico (Covington and Moore 1994, Allen et al. 1998, Mast et al. 1999, Moore et al. 1999), for some sites in the Colorado Front Range (Veblen and Lorenz 1991, Brown et al. 1999, Kaufmann et al. 2000), and for portions of the Bitterroot Range in Montana (Gruell 1983, Arno et al. 1995). As a consequence of fire suppression, the size and occurrence of high-severity fires has increased in this forest type. Reduction of ladder fuels through mechanical thinning and prescribed fire can effectively reduce the unprecedented occurrence of extensive crown fires and restore the historical surface fire regime in dry, low-elevation ponderosa pine forests (Covington et al. 1997, Allen et al. 2002, Fule et al. 2002).

Case study: The 2002 Rodeo-Chediski fire complex. The Rodeo-Chediski fire, which burned 189,095 ha in northern Arizona from 18 June through 7 July 2002, was the largest Arizona fire in recorded history. The area burned was dominated by ponderosa pine, with isolated pockets of mixed conifers at higher elevations along the Mogollon Rim, where the northern half of the fire burned. Fire-history studies conducted before the fire, in nearby ponderosa pine stands, record frequent surface fires with mean fire intervals of 7 to 10 years (based on fires recorded by more than 10% of sampled trees in 10- to 100-ha study areas; Swetnam and Baisan 1996). In 2002, high-severity crown fire affected 48% of the Rodeo-Chediski fire area, an extent of severe burning that is unprecedented in the low-elevation, dry ponderosa pine forests of this area.

The summer of 2002 marked the fourth year of drought in the Southwest. That May had been the second driest on record across Arizona and New Mexico in 108 years. Levels of fuel moisture before the fire were unusually low: 7% in 1000-hour fuels, as low as 2% in 10-hour (0.6- to 2.4-cm diameter) and 100-hour fuels, and below critical thresholds in live pine and brush fuels (Wilmes et al. 2002). The Haines index is a measure of lower-atmosphere stability and dryness correlated with wildfire growth. Low values (2 or 3) indicate moist, stable conditions; the highest values (5 or 6) represent dry, unstable conditions that favor moderate to high fire activity. The Haines index was 6 on many days during the Rodeo-Chediski fire.

Prescribed fire, salvage logging in previously burned stands, and fuel-reduction treatments (including the removal of slash, or woody debris, from branches and treetops) were effective in reducing fire severity and spread in the Rodeo-Chediski fire, even under extreme weather conditions (figure 7; Wilmes et al. 2002), as predicted by restoration research in Arizona (Fule et al. 2002). High-severity crown fires affected 35% of the stands that had been treated within the last 15 years, compared with 55% of the untreated stands. The average stand density of treated and untreated stands was 387 and 1108 trees per hectare, respectively. All prefire fuel treatments appeared to lower burn severity except for precommercial treatments, which increased it. In precommercial treatments, slash (branches and tree tops) was lopped and scattered throughout the stand, which contributed to higher fuel loads than those in untreated stands. Areas that had high forage production and low tree density experienced less severe burning during the Rodeo-Chediski fire, suggesting that open stands with abundant fine surface fuels were more resistant to high-severity canopy fire (figure 8). Overall, burn severity was positively correlated with overstory tree density (Wilmes et al. 2002). This outcome, in clear contrast with the findings from Yellowstone (where weather rather than fuel type and arrangement influenced fire behavior), highlights the heterogeneity of forest types and fire effects across the Rocky Mountain region.

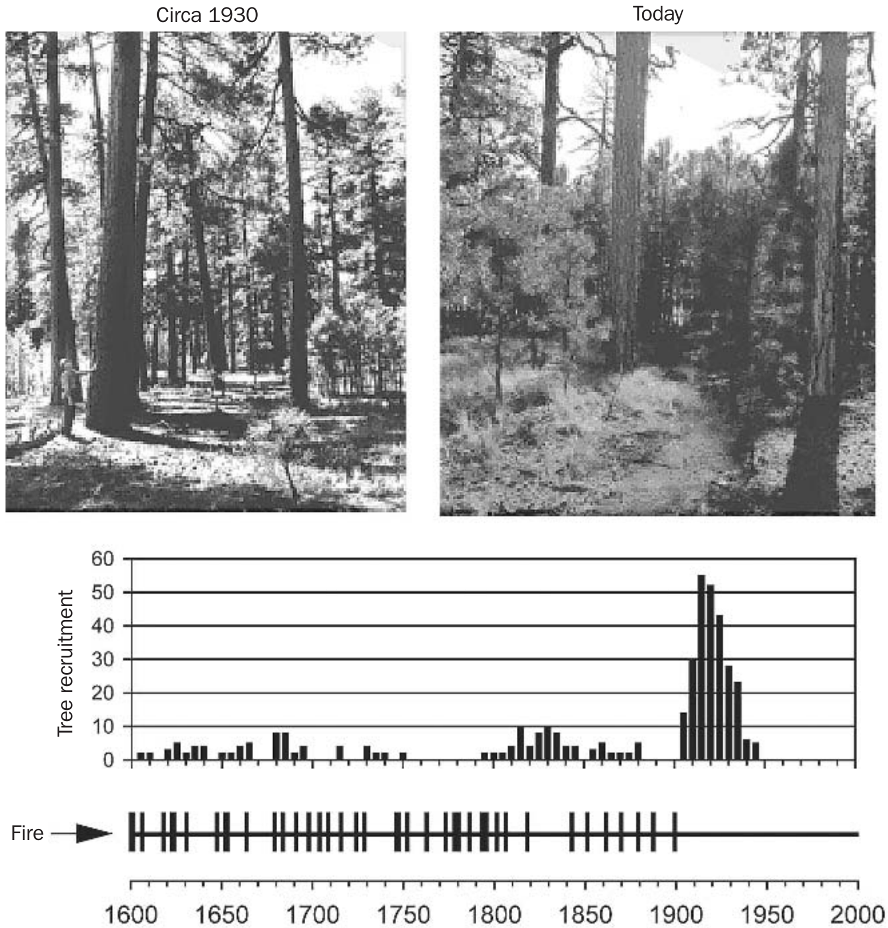

Figure 6. A comparison of historical and contemporary stand structure of dry ponderosa pine stands from the Jemez Mountains of New Mexico, and the relationship of this change to the frequency of low-severity surface fires. Source: Modified from Allen et al. 1998.

Summary: Low-severity fire regimes in low-elevation ponderosa pine forests. Dry, low-elevation ponderosa pine forests in the Rocky Mountain region, which were historically characterized by frequent low-severity fire regimes, make up an estimated 19% to 37% of the forested area that encompasses the three forest types discussed in this article (table 1). Such historically sparse forests, subject to high-frequency fires, comprise much of the ponderosa pine forest in Arizona and New Mexico but only a small fraction of the ponderosa pine forest in the central and northern Rockies. Regional modeling of fire regimes, based on a large fire-history database from the western United States, similarly predicts decreasing fire frequency from southern to northern latitudes (McKenzie et al. 2000). Important lessons about fire regimes in dry, low-elevation ponderosa pine forests are listed below.

- The historical fire regime in these forests was characterized by frequent, low-severity surface fires.
- Historically, the frequency, size, and severity of fires were largely controlled by spatial and temporal variation in fine fuels.
- Fire suppression has significantly increased tree densities and ladder fuels in low-elevation ponderosa pine forests.
- As a consequence of this change in stand structure, unprecedented high-severity fires now occur.

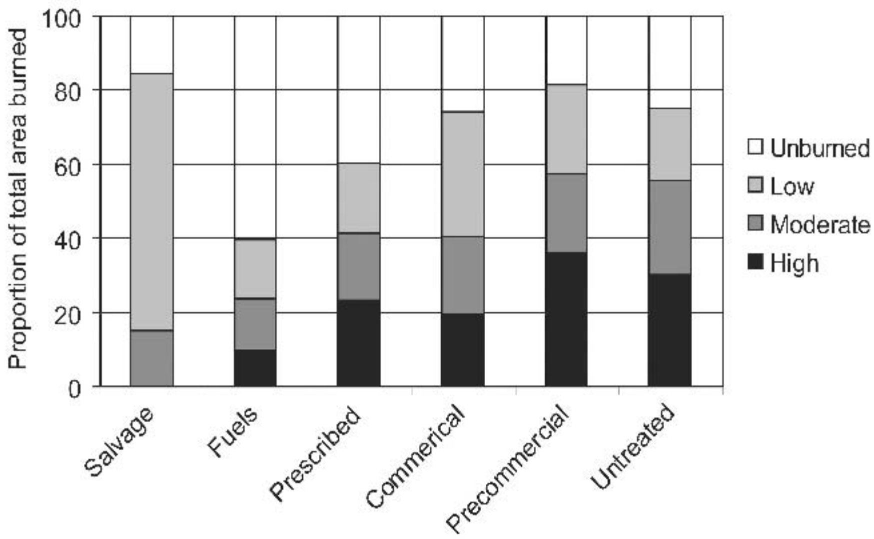

Figure 7. Proportion of different prefire fuel treatments burned at different severities during the Rodeo-Chediski fire in the Apache-Sitgreaves National Forests, Arizona, 2002. Burn severity, defined by the Burned Area Emergency Rehabilitation team* (www.fs.fed.us/r3/asnf/salvage/publications/proj_record/001_rodeo_baer_report_7-29-02.pdf), *ranges from unburned (surface fire with little or no canopy damage, tree foliage unscorched) through low severity (some tree crowns scorched but most trees not killed) and moderate severity (variable tree mortality, foliage scorched but not consumed) to high severity (complete tree mortality, foliage completely consumed). Fuel treatments are defined as salvage (removal of trees after a fire), fuels (thinning, chipping, and pile burning), prescribed fire (broadcast burning), commercial (removal, seed cut, regeneration, harvest, partial removal, final cut, or thinning), or precommercial (thinning with chipping, lopping, or both; no slash removal). Data are from Wilmes and colleagues (2002).

- Fuel-reduction treatments involving mechanical thinning and prescribed fire are likely to be effective in mitigating extreme fire behavior and restoring this forest type to the historical fire regime.

Mixed-severity fire regimes

Mixed-severity fire regimes are intermediate between the infrequent, high-severity fire regimes of high-elevation subalpine forests and the frequent, low-severity fire regimes of dry, low-elevation ponderosa pine forests. Both high- and low-severity fires can occur at varying frequencies in mixed-severity fire regimes. This fire regime occurs predominantly at mid elevations, where topographic variation creates a complex moisture gradient resulting in a mosaic of tree species and densities that is sometimes referred to as mixed conifer forest. There is also evidence of mixed-severity fire regimes that predate fire suppression in some forests dominated by ponderosa pine, and even in pure or nearly pure ponderosa pine stands at low to mid elevation (Veblen and Lorenz 1986, Mast et al. 1998, Kaufmann et al. 2000, Ehle and Baker 2003).

Historically, forests that experienced mixed-severity fire regimes had variable densities of ponderosa pine, Douglas fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), and western larch (*Larix occidentalis*), depending on their location. These forests constituted a mosaic of even-aged stands resulting from stand-replacing fire, interspersed with uneven-aged stands that experienced low-severity surface fires and episodic tree regeneration (Arno 1980, Brown et al. 1999, Kaufmann et al. 2000). Pre-1900 stand-replacing fires in these forest types have been documented by historic photographs and by the occurrence of even-age stand structures whose age corresponds to that of fire scars on adjacent trees (Gruell 1983, Veblen and Lorenz 1986, 1991, Arno et al. 1995, Swetnam and Baisan 1996, Shinneman and Baker 1997, Mast et al. 1998, Brown et al. 1999, Kaufmann et al. 2000, Ehle and Baker 2003). Low-severity fires are also well documented by historic photographs, fire scars, and all-age stands that include centuries-old trees, although these surface fires usually occurred less frequently than in the lower-elevation dry ponderosa pine forests described above (Arno 1980, Veblen and Lorenz 1991, Swetnam and Baisan 1996, Brown et al. 1999, Moore et al. 1999, Kaufmann et al. 2000, Veblen et al. 2000). The relative importance of surface versus crown fires and the size of these postdisturbance patches in shaping forests of mixed-severity fire regimes remain uncertain and have probably varied spatially and temporally.

Since the late 19th century, the densities of relatively fire-intolerant and shade-tolerant species, such as Douglas fir and grand fir, have increased in response to the suppression of low-severity fires in areas that historically experienced mixed-severity fire regimes (Arno et al. 1995, Kaufmann et al. 2000). Increases in density probably have occurred more commonly at lower elevations, on drier aspects, and adjacent to grasslands where frequent, low-severity fires were more dominant historically. Sites that previously supported denser stands because of favorable topographic and edaphic conditions have probably changed less as a result of fire suppression; those sites historically experienced stand-replacing fires, and high stand densities are a normal part of the postfire recovery process (Veblen and Lorenz 1986, Arno et al. 1995, Mast et al. 1998, Kaufmann et al. 2000, Ehle and Baker 2003). With fire suppression, forests that historically experienced mixed-severity fire regimes have developed a more homogenous forest structure across the landscape, resulting in larger areas of continuously dense forest and perhaps in larger patches of crown fire than were witnessed historically. In some areas, tree regeneration following logging of these forests in the late

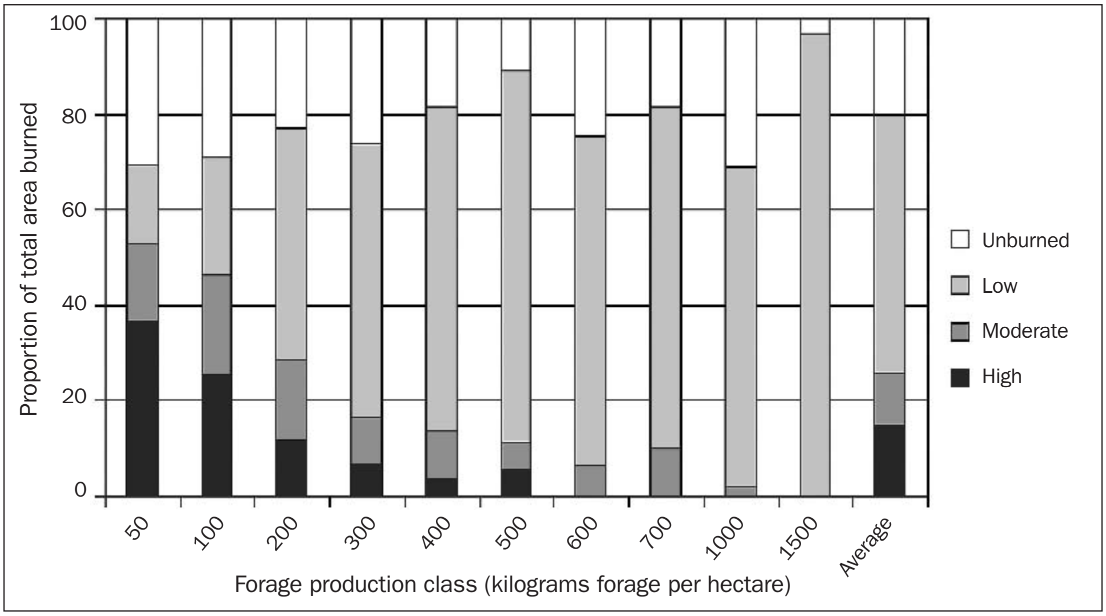

Figure 8. Proportion of different forage production classes burned at different severities during the Rodeo-Chedeski fire in relation to forage production classes for Carlisle and Town Tank allotments on the Lakeside Ranger District, Apache-Sitgreaves National Forest. Data are from Wilmes and colleagues (2002).

19th and early 20th centuries has contributed to high stand densities (Veblen and Lorenz 1986, Kaufmann et al. 2000). Overall, fire suppression has probably significantly affected only sites within the mixed conifer zone at lower elevations, on drier aspects, and adjacent to grasslands where fires historically were more frequent. Therefore, current fire regimes and stand densities in mixed conifer forests are likely to be within the historical range of variability, or at least are not likely to be as far outside this range as those in the dry ponderosa pine forests discussed above (Veblen 2003). However, additional research is needed on the causes of variability in mixed-severity fire regimes and the attendant effects of fire suppression.

In mixed-severity fire regimes, climate and fuels interact in a complex manner to control the frequency and severity of fires. Arno (1980) describes this interaction in mixed-severity fire regimes: "Under severe burning conditions, especially with strong winds, fires sometimes crowned and covered sizeable areas. When conditions moderated, fire would creep along the ground, with occasional flare-ups. Often the major fires burned at several intensities in reaction to changes in stand structure, fuel loadings, topography, and weather. The result was a mosaic of fire effects on the landscape" (p. 463). In mixed-severity regimes, in contrast to the previous two types of fire regime discussed, both climate and fuels (surface and ladder fuels) vary considerably and are important drivers of fire frequency and severity. We look to the example of the Hayman fire to tease apart these interactions in more detail.

Case study: The 2002 Hayman fire. The Hayman fire burned a 55,915-ha area southwest of Denver, Colorado, where previous fire history and forest structure studies (Brown et al. 1999, Kaufmann et al. 2000), mechanical fuel treatments, and burns (wild and prescribed) had occurred. Making use of this unplanned experiment, researchers assessed the relative effect of fuels and climate on fire behavior in the area, which had a historical mixed-severity fire regime (Finney et al. 2003).

Short-term drought during the 5 years before the fire created important antecedent conditions. In particular, below-normal precipitation and unseasonably dry air masses had persisted since 1998, when drier-than-average La Niña conditions began to develop. These conditions persisted intermittently through the spring of 2002. As a consequence, the Colorado Front Range received low snow during the winters of 2001 and 2002, with snowpack recorded in May 2002 at less than 50% of normal levels. By spring 2002, measurements of large-fuel moisture (moisture in 100-hour and 1000-hour fuels) in mid- to low-elevation forests of the southern Rockies were among the driest in the previous few decades, dipping as low as 3% when typically they exceed 12% (Graham 2003).

The size and severity of the Hayman fire can largely be explained by the extreme fire activity during two separate periods associated with sustained, exceptionally dry, forceful winds. First, on 9 June, the fire grew from 485 to 24,700 ha (43% of the total fire size); later, on 18 June, it traveled 5 miles along its southeastern flank (figure 9). During these two periods, mean relative humidity dipped below 8%, maxi-

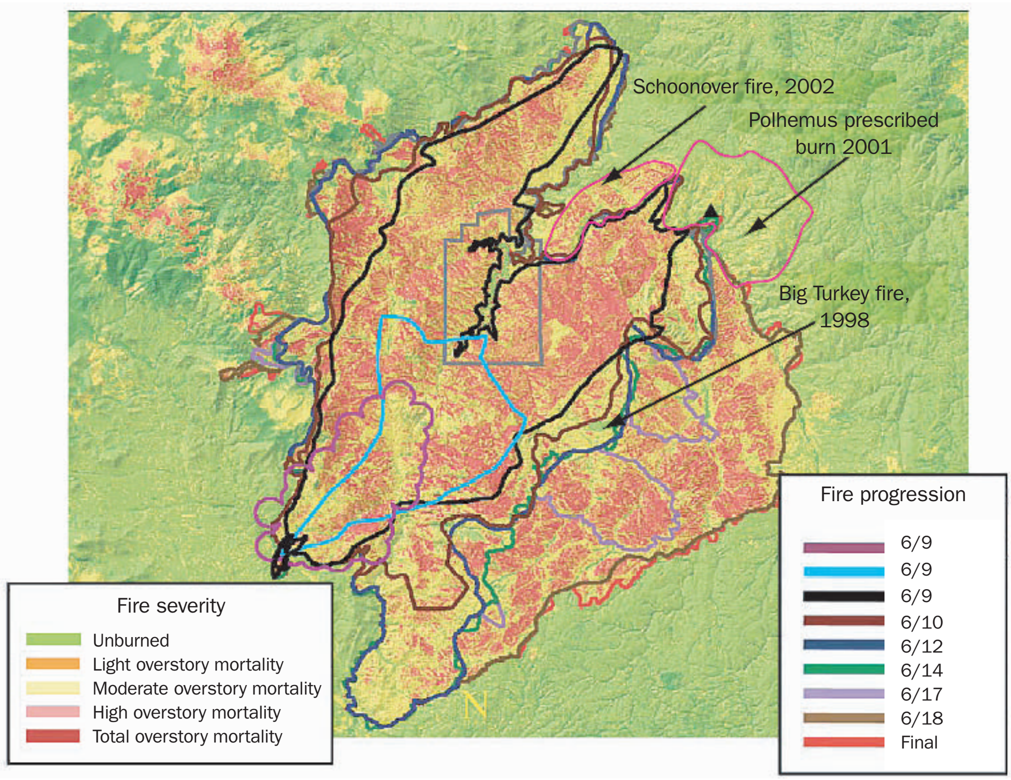

Figure 9. Map of the Hayman fire progression during the period 9–18 June 2002. Note the significant progress of the fire on 9 June (black line) and 18 June (brown line). Not all days are shown, because fire perimeters on slow-growth days overlapped previous days. Burn severity classes are based on the difference-normalized burn ratio from the US Geological Survey's National Burn Severity Mapping Project. Gray line represents the Cheesman Reservoir boundary, pink lines represent the perimeter of recent burns. Source: Modified from Finney and colleagues (2003).

mum wind gusts reached 84 miles (135 km) per hour, and the Haines index was 6, marking very dry, unstable conditions conducive to high fire spread. Both periods produced extensive torching, crown fire, and spotting (firebrands thrown in advance of the fire). These high-activity periods terminated with the passage of fronts followed by upslope winds that substantially increased ambient relative humidity (Finney et al. 2003).

During the substantial fire-progression days of 9 and 18 June, most fuel treatments had very little impact on the severity or direction of the fire (Finney et al. 2003). On 9 June, for example, the burned area included more than 2400 ha that had experienced previous prescribed fires or other fuel-reduction treatments. These treatments, which included previous wildfires (in 1963 and 1998), prescribed fires (in 1990, 1992, 1995, and 1998), and numerous stand modifications with and without subsequent slash removal (table 2), had virtually no effect on the Hayman fire. This is in marked contrast to the behavior of the Rodeo-Chediski fire, whose severity was affected by previous fuel-reduction treatments even under extreme climate and weather conditions. In the Hayman fire, extreme weather conditions overwhelmed the effectiveness of most fuel treatments. However, the fire stopped abruptly at the edge of the area that had been burned by two fires months to weeks before, in fall 2001 (Schoonover fire) and May 2002 (Polhemus prescribed burn), where very little fuel had accumulated during a spring of extreme drought (figure 9; Finney et al. 2003). Overall, the direction, severity, and size of the fire on extreme days were mostly explained by high wind and low relative humidity (table 3), with little effect of past fire or thinning activity. The Hayman review team concluded that "fuel modifications generally had little influence on the severity of the Hayman Fire during its most significant run on June 9th" (Finney et al. 2003) but acknowledged that the small size of these treatments contributed to their lack of effectiveness. On days of moderate fire growth, however, fuel modifications did influence fire spread and severity; of these modifications, recent wild or prescribed fires and thinning with slash removal were most effective. In an example of the interactions between fuels and climate, on 17 June the Hayman fire split into two runs on either side of the area burned by the Big Turkey fire in 1998 (figure 9); however, when the weather became more extreme the following day, this effect on fire shape and extent was obliterated (figure 9; compare 17 June and 18 June perimeters).

Table 2. Distribution of fire severity classes among fuel-modified areas on moderate slopes (defined as slopes of less than 30%) that burned in the Hayman fire on 9 June 2002.

Level of prefire fuel modification	Area (ha)	Fire severity class (percentage)			
		Unburned	Low	Moderate	High
Unmodified	9128	4	18	8	70
		Recent modifications (after 1990)			
Wildfires	5	0	0	25	75
Prescribed fires	291	6	20	11	63
Fuel treatment	0	NA	NA	NA	NA
Improvements and treatment	160	0	19	7	74
Improvements, no treatment	253	3	12	9	76
Harvest and treatment	657	5	14	10	71
Harvest, no treatment	236	0	1	33	66
Plantation	55	0	8	5	87
		Older modifications (before 1990)			
Wildfires	Unknown	NA	NA	NA	NA
Prescribed fires	34	17	50	8	25
Fuel treatment	2	0	86	14	0
Improvements and treatment	0	NA	NA	NA	NA
Improvements, no treatment	592	1	14	8	77
Harvest and treatment	1	0	16	9	75
Harvest, no treatment	384	3	27	2	68
Plantation	127	0	27	10	63

Source: Finney et al. 2003.

Summary: Mixed-severity fire regimes in the Rocky Mountain region. Mixed-severity fire regimes account for an estimated 17% to 50% of the forested area in the Rocky Mountain region that encompasses the three major forest types discussed in this article (table 1). These forests experience the most complex type of fire regime and the least understood. Nonetheless, we have learned several important lessons about mixed-severity fire regimes in Rocky Mountain forests.

- The historical fire regime in these forests is complex, including both low-severity surface fires and infrequent high-severity crown fires.
- Both fuels and climate have major influences on the frequency, severity, and size of fires.
- Fire suppression has had variable effects on fuel densities in mixed-severity fire regimes, with the greatest impacts on sites that formerly supported open woodlands.
- The occurrence of high-severity crown fires is not outside the historical range of variability, although their size and frequency may be increasing.
- Extreme climate and weather conditions can override the influence of stand structure and fuels on fire behavior.
- Fuel-reduction treatments (mechanical thinning and prescribed burning) may effectively reduce fire severity under moderate weather conditions, but these treatments may not effectively mitigate fire behavior under extreme weather conditions and may not restore the natural complexity of historical stand and landscape structure.

Implications for fire mitigation and restoration

What does an understanding of the spatial variation in dominant controls on wildfire frequency and severity mean for ecological restoration and for effective fuel treatments to reduce the threat of large, severe wildfires? The Yellowstone fires in 1988 revealed that variation in fuel conditions, as measured by stand age and density, had only minimal influence on fire behavior. Therefore, we expect fuel-reduction treatments in high-elevation forests to be generally unsuccessful in reducing fire frequency, severity, and size, given the overriding importance of extreme climate in controlling fire regimes in this zone. Thinning also will not restore subalpine forests, because they were dense historically and have not changed significantly in response to fire suppression. Thus, fuel-reduction efforts in most Rocky Mountain subalpine forests probably would not effectively mitigate the fire hazard, and these efforts may create new ecological problems by moving the forest structure outside the historic range of variability (Veblen 2003, Romme et al. 2004).

In contrast, for many low-elevation, dry ponderosa pine forests, it is both ecologically appropriate and operationally possible to restore a low-severity fire regime through thinning and prescribed burning (Covington et al. 1997, Allen et al. 1998, 2002). Fuels rather than climate appear to be the most significant factor affecting fire spread and severity in these forests. Fire suppression in dry ponderosa pine forests appears

Table 3. Comparison of the mean and range of weather indices associated with the type (high, moderate, or low) of fire-growth days during the Hayman fire, 9 June to 18 June 2002.

		Mean (range)			
Fire-growth days	*n*	Relative humidity (percentage)	10-minute average wind (kph)	Maximum wind gust (kph)	Haines index
Low	4	36.6 (8–68)	11.2 (0–30.4)	22.4 (3.2–57.6)	3.7 (2–6)
Moderate	4	27.6 (5–76)	11.2 (0–28.8)	24 (1.6–54.4)	4.2 (2–6)
High	2	7.8 (5–15)	16 (1.6–48)	38.4 (3.2–134.4)	5.7 (5–6)

kph, kilometers per hour.

Note: The Haines index, ranging from 2 to 6, measures the moisture and stability of the lower atmosphere; low values indicate moist, stable conditions, and high values indicate dry, unstable conditions conducive to fire. The two high fire-growth days occurred on 9 and 18 June. High- and moderate fire-growth days are identified on the Hayman fire progression map (figure 9); low fire-growth days are those omitted from the map because fire perimeters were not significantly different from previous days. Data are summarized from Finney and colleagues (2003).

to have contributed to an unprecedented buildup of fuels and to the occurrence of high-severity fires. Indeed, the objectives of fire mitigation and forest restoration generally converge in forests of this type.

Perhaps the most difficult forests to assess are the mid-elevation forests that historically were characterized by mixed-severity fire regimes. Because mixed-severity fire regimes are most complex and least well understood, we must exert caution in developing simple prescriptions for wildfire mitigation that may not bring predictable results under extreme climate conditions. Our analysis reveals that fire regimes, climate, fuel type and abundance, and stand structure vary significantly across the Rocky Mountain region. As a consequence, the heterogeneous forests in this region require very different approaches to restoration and wildfire management (Gutsell et al. 2001). Clearly, policymakers need to incorporate ecological heterogeneity into their decisions in order to implement sound forest management policy.

In addition to the fuel-management operations described above, we need new research to clarify the geographic variation in fire regimes across different forest types in this large, heterogeneous region. There is great geographical variation in the distribution of the three broad fire regimes defined here. In Montana, for example, subalpine forests cover roughly 40% of the forested area, while in Arizona the extent of these forests is significantly smaller and they are more isolated on scattered mountaintops. At a regionwide scale, it is difficult to define the precise extent of these different fire regimes and their spatial location (and especially to distinguish between the low-severity and mixed-severity fire regimes), as illustrated by the variation between the estimates based on PNV groups and those based on current cover type (table 1). There is also significant variation in fire regimes within each of the three broad fire-regime classes in response to local topography and landscape position, and there are other important vegetation types not covered in this brief article (e.g., piñon-juniper woodlands; Romme et al. 2003).

A "one size fits all" approach to reducing wildfire hazards in the Rocky Mountain region is unlikely to be effective and may even produce collateral damage in some places. We do not advocate delaying action until all of the ecological questions have been answered; in many places, there is an urgent need and a solid ecological basis for restoration and fire-mitigation efforts. In other areas, however, where the ecological basis for aggressive fuel reduction is inadequate or lacking, uncritical extrapolation of models from other systems may cause more harm than good.

Acknowledgments

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