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Synthesis, part of a Special Feature on The Conservation and Restoration of Old Growth in Frequent-fire Forests of the American West

Defining Old Growth for Fire-adapted Forests of the Western United States

Merrill R. Kaufmann [1], *Daniel Binkley* [2], *Peter Z. Fulé* [3,4], *Marlin Johnson* [5], *Scott L. Stephens* [6], *and Thomas W. Swetnam* [7]

ABSTRACT. There are varying definitions of old-growth forests because of differences in environment and differing fire influence across the Intermountain West. Two general types of forests reflect the role of fire: 1) forests shaped by natural changes in structure and species makeup—plant succession—that are driven by competitive differences among species and individual trees and by small-scale disturbances, and 2) forests where plant succession processes are disrupted by major biological disturbances (fire, insects, wind, or drought) extending across larger areas. Some case examples of old-growth forests where fire was historically frequent are used. The examples sketch out the typical biophysical settings, fire regime, natural disturbance factors, spatial features of patches, and the processes and conditions that produce spatial changes of the landscape over time. These examples confirm the complexity of describing or defining old growth in frequent-fire forests. We define fire-adapted forests at three spatial scales, whereas the standard definition of old growth refers to a patch or stand condition. Our definition is based on ecological principles rather than on the cultural aspects of old growth. It focuses on central tendencies, given all the possible combinations of conditions and processes, that move forests toward old growth in the fire-adapted forests of the Intermountain West.

Key Words: *fire-adapted forests; fire frequency; fire intensity; fire interval; fire severity; old-growth forests; old-growth landscapes; old-growth patches; old-growth stands*

INTRODUCTION

There are two broad types of forests that reflect different roles for fire. Some forests are shaped over time by the natural competitive differences among species and individual trees and by small-scale disturbances affecting one or a few trees at a time. In other forests, plant succession processes are disrupted with some regularity by major biological disturbances, such as fire, insects, wind, or even drought, that extend across larger areas. Because each of these broad types includes old-growth forests, we might expect difficulty finding a single definition of old growth suitable for all forests.

Forests in the coastal Pacific Northwest and other areas where climates are wet are typical examples of forests driven largely by natural plant succession and small-scale disturbances. Such forests usually have an overstory dominated by large, old trees with multiple layers of younger, smaller trees beneath the overstory ready to replace the large, old trees when they die. Because these forests rarely become very dry and fire is unlikely for three or more centuries, there often is a large amount of decaying wood from fallen trees.

But the Pacific Northwest model of old-growth forests is not appropriate for forests where fire is a frequent ecosystem process (Kaufmann et al. 1992). In drier regions, forest types have evolved more in response to disturbance by fire than in response to successional processes in the absence of fire. Old trees become a part of such forests because of adaptations that allow them to survive all but the most severe fires. Just as there are many different types of forests for the diverse array of climates, soils, and topography in the western United States,

[1]U.S. Forest Service (retired), [2]Colorado Forest Restoration Institute, [3]Northern Arizona School of Forestry, [4]Ecological Restoration Institute, [5]U.S. Forest Service, Southwest Region, [6]University of California Berkeley, [7]Lab of Tree Ring Research, University of Arizona

there are many different types of old-growth forests. Except for the moist, coastal regions of the West and high-elevation forests of the Rocky Mountains, there is a wide array of forests that experience fire relatively frequently (i.e., <35-year intervals). These forests include, among others, ponderosa pine (*Pinus ponderosa*) in a number of different climatic regions in the West; giant sequoia (*Sequoiadendron giganteum*)–mixed conifer forests in California; and mixed-conifer forests with ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), true firs (*Abies* spp.), and other species in the southern and central Rockies and the San Francisco Peaks near Flagstaff, Arizona.

Recognition of the keystone role of frequent surface fire in ponderosa pine dynamics was seminal in a revolution of fire ecology understanding, and in fire management practices, in the mid- and late-20th century. Harold Biswell, Gus Pearson, Harold Weaver, and Charles Cooper, to name just a few of the early scientists who studied ponderosa pine, developed a general paradigm of ponderosa pine forest structure and dynamics, although not consistently with an eye to fire ecology. This paradigm has generally continued today as a basic foundation of our understanding, but with some important modifications in the last decade. The most common description of natural and old-growth ponderosa pine forests is that they are “uneven-aged stands composed of relatively small, even-aged groups.” Park-like forests with open canopies and grassy understories were typical in the more productive stands of northern Arizona and New Mexico. A variety of other conditions occurred in less productive, rockier, or steeper terrains, where understory grass cover was sparser and shrub layers became more common.

No single definition for old growth is adequate for this broad assortment of forests and climatic conditions (Kaufmann et al. 1992). That said, however, it has been assumed, all too often, that old-growth forests should all be like those in the Pacific Northwest. For several decades, national debate about forest management focused on those forests, and some of the best contemporary descriptions of old-growth features came out of those discussions. In this chapter, we focus on the features and characteristics of old-growth forests found where fire is an important and relatively frequent component of the forest environment.

ECOLOGICAL AND CULTURAL IMPORTANCE OF OLD GROWTH

The key structural and functional feature of old-growth forests in frequent-fire landscapes is the fine-scale diversity of groups of big trees interspersed with grassy openings or canopy gaps (see article by Binkley et al. in this issue). For example, a hectare of old-growth forest might have 15 patches of trees, with each patch covering about 0.05 ha. Tree canopies would cover about one-third of the stand, with canopy openings comprising other two-thirds. This fine-scale pattern would result in 180–370 m of edges between tree patches and openings (note, however, that considerable variation exists among frequent-fire, old-growth forests). Understory vegetation would do well in this forest, as would animal species that depend on understory vegetation. Animals that can use fairly open clumps of trees may also do well, but this structure would not support species that require dense forests.

Forested landscapes in most of the frequent-fire ecosystems in North America have been influenced by humans for many centuries. Burning by Native Americans, both accidental and planned, happened extensively during the past 10 000 or more years. Although humans directly modified fire regimes and forest conditions in many places and times, their effects were not spatially or temporally uniform, and some forest landscapes with plenty of lightning and infrequent human visitation were not significantly altered by human fire uses.

Old growth has been defined many times and in many ways. It is difficult to write a definition of old growth that will be applicable to all forests. To some people, old growth is simply a forest that has not been disturbed by logging. “Untrammeled by man,” “cathedral old growth,” “legacy forests,” and other terms come to mind.

DEFINITIONS

Traditional and Emerging Definitions and Descriptions of Old Growth

Old-growth forest definitions have varied during the last two decades (Frelich and Reich 2003). Public and scientific interest in United States’ old-growth forests began in the Pacific Northwest. Early old-growth definitions targeted coastal Douglas-fir and western hemlock (*Tsuga heterophylla*) forests that were the main habitat of the northern spotted owl (*Strix occidentalis caurina*). One early definition (1989) developed by Jerry Franklin and Thomas Spies (United States Department of Agriculture (USDA) 2003) from this period is:

> *Oldgrowth forests are ecosystems distinguished by old trees and related structural attributes...that may include tree size, accumulations of large dead woody material, number of canopy layers, species composition, and ecosystem function.*

Several international organizations have also defined old-growth forests, including:

> *Old-growth forest is forest which contains significant amounts of its oldest growth stage—usually senescing trees—in the upper stratum and has not been subject to any disturbance.* Department of Natural Resources and Environment, Victoria, Australia.

> *The old growth forests have been described by the adjective primeval, ancient, wilderness, virgin, pristine while in forester's terminology they are called as over-matured, decadent, and senescent, old growth. The old growth forests may be defined as a climax forest that has never been disturbed by man. The old growth forests can be classified as per the age and disturbance criteria.* European Environment Agency, Copenhagen, Denmark.

Both of these definitions are similar to that proposed by Franklin and Spies (1989) in that they mainly pertain to forests having no severe recent disturbance, and through time, succession produces large, old trees with multiple canopy layers.

Old-growth forests have been defined by the Society of American Foresters (Helms 1998) as:

> *The (usually) late successional stage of forest development. Old growth forests generally contain trees that are large for the species and site and sometimes decadent (over mature) with broken tops, often a variety of tree sizes, large snags and logs, and a developed and patchy understory. Due to large differences in forest types, climates, site quality, and natural disturbance history, (e.g., fire, wind, and diseases and insect epidemics), old growth forests vary extensively in tree size, age classes, presence and abundance of structural elements, stability, and presence of understory.*

More recently, Franklin, Spies, and Robert Van Pelt defined old-growth forests for the Washington State Department of Natural Resources (WSDNR 2005). They referred to forests on the west or east side of the Cascade Range as "westside" or "eastside," and noted large differences depending on forest type and natural disturbance regime:

> *Temperate old-growth forests are characterized by a high diversity of structures, and a high level of heterogeneity in the spatial arrangement of the individual structures. For example, old growth forests typically incorporate a variety of sizes and conditions of live trees, snags, and logs on the forest floor, including some specimens that are old and/or large for the forest type and site under consideration. Spatial heterogeneity is present vertically—in the form of a vertically continuous but variably dense canopy, and horizontally—apparent in patchiness (including gaps) in stand density.*

> *Old-growth conditions vary in detail among essentially all forest types in terms of their exact attributes, which is why type-specific definitions are necessary. However, old-growth conditions differ profoundly between moist westside forests, which are characterized by highly infrequent, stand replacement events, and dry eastside forests, which were characterized by frequent low-severity fire events. Patterns of old-growth forest structure differ dramatically between west- and eastside forests, reflecting the differing disturbance regimes. Westside forests are characterized by stand-replacement disturbance or tree reproduction regimes that occur at very long intervals; for example, return intervals of wildfire and severe windstorms in western Washington were typically 250 to more than 400 years. Dry eastside forests —specifically the ponderosa pine and dry mixed conifer plant associations—were*

subject to frequent, low to moderate severity wildfires that created small openings in the stand where tree reproduction could develop.

The recent definitions from the United States stress the differences in old-growth forests that occur in differing environments and fire regimes. This is critically important because old-growth forests that develop with a frequent, low- to moderate-severity fire regime will be profoundly different than those that develop in moist coastal areas of Oregon, Washington, and northwestern California or at higher elevations in the Rocky Mountains.

Keeping Track of Fire Intensity, Fire Severity, Fire Frequency, and Fire Interval

Four terms used to characterize a fire regime—fire intensity, fire severity, fire frequency, and fire interval—are often used interchangeably and incorrectly. To avoid confusion in our definitions and descriptions of old growth, we need to clarify what we mean by each term. Fire intensity refers to the energy release during the combustion process. Although fire intensity is important in understanding fire behavior and immediate effects, it is not a good descriptor of long-term fire consequences. Thus, the more important term for understanding ecological effects is fire severity, which is a function of fire intensity and duration. Fire severity refers to immediate and longer-term ecological consequences to vegetation (and soils) that stem from a fire event. Fire frequency refers to the number of fires occurring in a given period of time and area, and is closely related to fire interval, which refers to the time between fires in a given period of time and area.

Note that fire intensity, fire severity, and fire frequency each can be described as low, moderate, and high. In general, low-severity, low-intensity fires burn on or above the forest floor; moderate-severity, moderate-intensity fires are those that kill a portion but not all of the forest overstory; and high-severity, high-intensity fires are those that result in complete or nearly complete mortality of the overstory. Other definitions of severity may focus more on soil effects than on vegetation. Even a low-intensity fire can be severe if it lasts for a long time and burns deep into duff, killing trees due to lethal temperatures under the bark. Low-frequency fires typically are those occurring at least a century or more apart. Moderate-frequency fires have been described as those burning roughly every 35–100 years. And high-frequency (or simply frequent) fires are those burning less than 35 years apart, although we note that some of the most fire-dependent forests have very frequent fires (typically every 3–15 years). We caution that moderately severe fires and mixed-severity fires (those having areas of low, moderate, and high severity within their perimeter) are not the same thing.

Old-growth Patches, Stands, and Landscapes in Forests Experiencing Frequent Fire

Definitions specifically suited for fire-adapted forests are needed because definitions developed for forests experiencing infrequent fire are not appropriate. By their very nature, forests that experience more frequent fire are less dense and have smaller accumulations of vegetation and fuels beneath the forest canopy than forests growing in more moist climates and experiencing infrequent fire.

Standard definitions of old growth generally refer to a patch or stand condition, not individual trees. However, old trees can occur in smaller or larger spatial configurations that may also be termed old growth, namely patches and forests or landscapes. Alrhough old trees must exist for the term “old growth” to be relevant at all, “old” is a relative term that varies greatly among species (Swetnam and Brown 1992). An aspen (*Populus* spp.) tree may be relatively old at 100 years of age, but bristlecone pine (*Pinus longaeva*) may not be considered old until much, much later. In some species, rather distinct changes in appearance and structural features of individual trees occur at a fairly consistent age (e.g., about 200 years in ponderosa pine; Kaufmann 1996).

We define old growth in fire-adapted forests at three spatial scales, in each case referring to classical historical conditions as the basis for our definitions. Historical conditions include the forest structure, fire regime, and species composition that characterized these forests for millennia before grazing, fire suppression, and logging associated with industrialized society began in the late 1800s (Swetnam et al. 1999). Our definitions are derived from ecological rather than cultural features, and they focus on “central tendencies.” Although many exceptions exist that stem from natural variability, it is useful to define the more common ecological conditions encountered. Features at some spatial scales may not be useful at other scales. For example, Long and Smith (2000) evaluated landscape patterns in relation to goshawks (*Accipiter gentilis*) and restoration in southwestern ponderosa pine, and concluded that patches and clusters were useful, but stands were not. In other cases where fire creates and helps delineate rather uniform conditions across larger areas (large patch size in the landscape mosaic), the concept of stands seems more helpful. Thus, we recognize the following:

- Old-growth patches are groups of trees having similar characteristics and conditions. Such patches may include fairly similar tree ages and sizes or combinations of ages and sizes, limited amounts of dead and downed material, and dead trees and spike tops, but they are readily distinguished from adjacent patches having different characteristics.

- Old-growth stands are areas (generally >2 ha in size and possibly as large as 40 ha or more) that display somewhat uniform and consistent characteristics of old-growth patches as described above. The term “stand” may be more useful for management purposes than for describing the ecology of forests.

- Old-growth forests or landscapes contain sufficient numbers of patches and stands of old growth to be reasonably representative of the forest type in historical times. However, portions of the landscape may be in various stages of development (even temporary openings or patches of very young trees) to provide future old-growth patches in the landscape. Landscapes vary in size, but are generally considered to be at least as large as major natural disturbances, such as fire.

In some forests having frequent or moderately frequent fire, patches of trees regenerate at the same time and grow throughout their lifetime as a recognizable unit or cohort. A common distinguishing feature of individual patches in fire-adapted forests, regardless of patch size, is a maximum age (age cap) based on regeneration of trees after a past disturbance. These patches of trees can range from a few trees to up to 6–12 ha or more in size, but in many instances are between about 0.1 and 4.0 ha.

The arrangement of patches—the landscape mosaic—is not constant over time. Rather, natural processes, such as fire, insect activity, disease, wind, regeneration of new seedlings, and competition among individual trees, interact to maintain a variety of conditions across the landscape. Just as the components of patches, stands, and landscapes vary spatially, so do the characteristics of ecological processes vary with time. A wind event may be as brief as a moment or as long as hours or days, fire an hour or a day or months, drought a season or a year or more, regeneration a year or decades or a century or more, and reaching an old-growth condition a matter of centuries. Under the influence of climate and fire, the patches in the mosaic changed with time, and in a fully functioning ecosystem, the old-growth forest landscape was maintained even though the locations and proportions of various patch types varied. And through all the changes of fire-adapted forests, fire remained a primary factor that, with some regularity, shaped the spatial arrangement of patches and stands in the landscape.

ESSENTIAL AND NON-ESSENTIAL FEATURES OF OLD-GROWTH FORESTS

Given all the possible combinations of conditions and processes that affect forests and the development and maintenance of old growth, which structural features are considered to be essential for old growth to exist? Table 1 provides a brief evaluation of patch and stand features necessary for fire-adapted forests to be considered old growth.

SOURCES OF VARIABILITY AMONG FOREST TYPES AND REGIONS

Wide variations occur among forest types, including differences in fire interval, fire severity, patch size, species composition, typical age and size of old trees, and accumulation of woody debris. Table 2A lists typical ranges of these characteristics for fire-adapted forest types. Table 2B provides specific estimates for case examples we describe more thoroughly below. (Fig. 1, a diagram shown in the case studies section below, illustrates how different mixtures of patch types result in different conditions at a landscape scale, even within a forest type.)

Table 1. Essential structural features of old growth in fire-adapted forests. Note that whether or not a feature is essential may depend on scale, e.g., patch, stand, or landscape. For example, age variability is likely at a landscape scale, and snags and large dead and downed fuels may not exist in some patches.

Structural feature	Essential Structural Feature?	Comment
Large trees	No	Tree size depends on individual site characteristics (species, precipitation, soils, etc.) and competition. Young trees may be large, and old trees may be small.
Old trees	Yes	Trees develop structural characteristics that are relatively unique when old. Examples are dead tree tops, flattened crowns, different branch characteristics, diversity in crown form, altered bark color and texture.
Age variability	No	This is an additional feature in some old-growth forest types. Some forests regenerate episodically (even aged) with most trees establishing in a few years to a decade, probably in conjunction with wet years and large seed crops, and in concurrence with relatively long intervals between fires. Others may regenerate over decades (uneven aged).
Snags and large dead and downed fuels	Yes	Snags and large downed wood are essential elements of old forests, although frequent historical fires may have limited the accumulation of dead wood. The density and sizes of these features vary depending on forest type, precipitation, and other factors. Snags and large dead and downed fuels may be unevenly distributed across the landscape.
Between-patch structural variability	Yes	High variability is a critical feature of these forests. Within-patch variability may be low, but variation among patches is large. Proportions of patches with different developmental stages varies depending on forest type, climate, etc.

Several underlying conditions affect the variables reported for each forest type in Table 2. A thorough interpretation of these conditions is well beyond the scope of this article, but it is important in defining old growth to mention a few underlying factors that result in old-growth variability, both among and within forest types found across the interior West.

Latitude, elevation, and climate affect seasonal patterns of moisture and precipitation across the geographic range of fire-adapted forests in the western United States. In general, conditions become more moist and cooler at higher elevations and more northerly latitudes. However, El Niño cycles and monsoonal moisture flow into the Southwest do not reliably extend into the central, interior West; mountain ranges also cause significant rain shadows. Combined with effects on understory vegetation, these factors introduce considerable variability in fire regimes, and resulting patterns of old-growth patches in the landscape.

Understory vegetation and fuel loading vary with physical environmental differences described above. Grassy vegetation beneath trees is commonly associated with frequent, low-severity fires that generally burn every 2–15 years. These fires consume fuels that otherwise might accumulate and carry fires upward into the crowns of trees. In other areas, low precipitation and poor soils contribute to sparse mixtures of grasses and forbs that do not regularly support the spread of surface fires. Where fires are somewhat less frequent, shrub communities and accumulation of other fuels often result in hotter fires that kill even

Table 2. Features of typical old-growth forest types. (A) Generic features for moist and dry forest types; (B) features found in specific geographic regions reported in the section on case studies.

A. Generic descriptions

	Fire regime[1]			Old-growth Characteristics		
Forest type	Intervals (yrs.)	Severity	Typical patch (ha)[2]	Tree Species	Ages[3]	Woody debris[4]
Coastal, moist	200–300+	high	100s–1000s	Douglas-fir, hemlock, red cedar	200–300+	very extensive
Mixed conifer, moist	35–75+	mixed	1s–100s	Douglas-fir, white fir, pines	150–300+	extensive
Mixed conifer, dry	10–35	mixed	0.08–2	Douglas-fir, white fir, pines	150–300+	moderate to extensive
Semi-arid/arid woodlands, warm	10–100s	high	10s–1000s	pinyon pine, juniper	100–300+	low to high productivity
Semi-arid/arid woodlands cold	500+	mixed	single tree	bristlecone pine, whitebark, foxtail	300–1000+	low extent, scattered
Ponderosa pine, moist	15–50+	mixed	0.08–12	ponderosa pine, Douglas-fir	200–400+	low extent, very scattered
Ponderosa pine, dry	2–15	low	0.04–0.08	ponderosa pine	200–400+	low extent, very scattered

B. Geographic specific descriptions

	Fire regime			Old-growth Characteristics			
Forest type	Intervals (yrs)	Severity	Typical patch (ha)	Ages	Min. sizes[5]	Woody debris accumulation	Canopy variability[6]
Giant sequoia/ mixed conifer	2–35	low/mixed	0.04–2	500–3000+	180+ cm	moderate, scattered	high
Southwest ponderosa pine	2–15	low	0.04–0.8	200–300+	50+ cm	low, scattered	moderate
Front Range ponderosa pine	30–70	mixed	0.8–12	200–500+	30+ cm	moderate, scattered	high
Northern Rockies mixed conifer	25–40	low/mixed	1s–100s	200–500+	40+ cm	moderate, scattered	high

(con'd)

East-side ponderosa/ Jeffrey pine	3–25	low	0.004–1.2	200–400+	40+ cm	low, scattered	moderate

Footnotes:
[1] Fire regime characteristics are generalized to typical ranges of intervals between widespread fire events at the stand level (i.e., 4.0–40 ha) and fire severity on a qualitative scale of low, mixed, and high. Mixed severity refers to a combination of fire severities, including some high-severity burn areas within a matrix of low- and moderate-severity burn areas.
[2] Typical patch (or stand) sizes refer to the area occupied by even-aged or relatively even-aged groups of trees. These may be cohorts that established within a period of time following a disturbance, such as fire or insect outbreak.
[3] Ages of trees include minimum ages of oldest trees in the patch or stand identified as old growth.
[4] Wood debris accumulation refers to snags, logs, and branch material in the patch or stand.
[5] Minimum sizes are diameters at breast height of the largest trees in the patch or stand identified as old growth.
[6] Canopy variability refers to heterogeneity of the canopy structure on a qualitative scale (high, moderate, low), with high variability indicating multiple canopy layers across most of the patch or stands, moderate indicating multiple canopy layers in part of the patch (but less than half), and low indicating typically a single canopy layer throughout a patch or stand.

widely spaced trees and often create openings. Furthermore, survival of a portion of overstory trees may lead to scattered old trees that are relics of former patches. Variable spatial and temporal patterns of tree survival during fire events and uneven establishment of new seedlings after fires combine to create considerable heterogeneity and complexity in some old-growth landscapes (Fig. 1). Historical ponderosa pine–Douglas-fir forests in the Colorado Front Range are a good example of this complexity.

Other disturbances associated with fire behavior include mortality from insects and disease, drought, and wind, each of which affect both stand density and fuel structure of patches and stands.

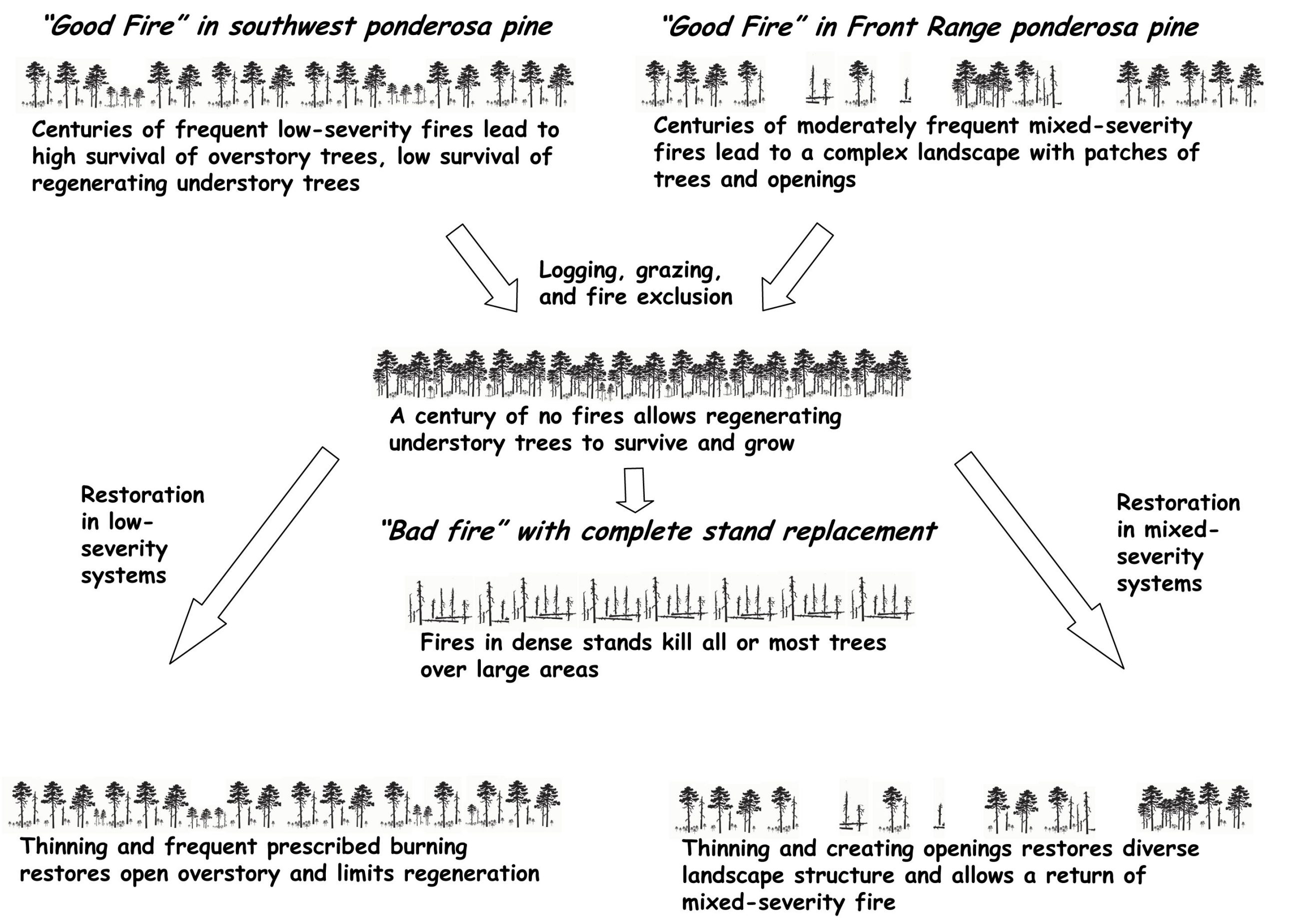
Weather during fire events may be a major source of variation in fire outcomes. Fires in historical ponderosa pine–Douglas-fir forests typically burned for months. During this time, weather conditions may have varied from moist, cool, and calm to dry, hot, and windy. Day-to-day differences in rates of fire spread and fire intensity undoubtedly contributed to the mixed-severity behavior of fire and resulting complex landscape patterns in many locations.

Each old-growth forest type in Table 2 and each case example discussed below undoubtedly varied in one or more of the factors discussed above. Furthermore, the significant role fire played in historical fire-adapted landscapes prevented many forests from reaching a successional climax in which the structure and composition of the forest would have stemmed from site suitability of species and individual-tree competition in the absence of fire.

CASE EXAMPLES OF OLD-GROWTH FORESTS WHERE FIRE WAS HISTORICALLY FREQUENT

We noted earlier that old-growth forests occur in a wide range of settings, and arriving at a simple unifying definition of old growth is difficult. In this section, we briefly describe old growth in several forest types to illustrate how differences in conditions commonly encountered in frequent-fire

Fig. 1. Comparison of historical, current, and restored ponderosa pine landscapes in the Southwest (left) and Colorado Front Range (right).



forests of the western United States help distinguish various kinds of old-growth forest ecosystems. Our descriptions focus specifically on historical conditions because they provide useful insights into future needs for restoring ecologically sustainable landscapes and for conserving biodiversity. For each forest, we provide a typical geographic location or biophysical setting, the fire regime, other prominent natural disturbance factors, spatial features of patches, and the processes and conditions that produce spatial changes across the landscape over time.

Giant Sequoia–Mixed-conifer Forests of the Sierra Nevada

Key historical features were high- to moderate-frequency surface fires, and variable patterns of tree establishment, producing small-sized groups of similar-aged giant sequoias in the overstory, and a secondary canopy layer of sugar pine (*Pinus lambertiana*), ponderosa pine, white fir (*Abies concolor*), and incense cedar (*Calocedrus decurrens*).

Giant sequoia–mixed-conifer forests are found exclusively in about 75 distinct groves at mid-elevations (1500–2300 m) on the west slope of the Sierra Nevada in California. Although this type occupies a relatively small area of landscape, it looms large as archetypal old-growth forest, with the world's largest trees and some of its oldest. A number of national parks and monuments (e.g., Sequoia, Kings Canyon, and Yosemite), California state parks and forests, and national forests contain giant sequoia groves, and millions of visitors enjoy recreation in these areas each year. These are among the most productive conifer forests in the world, with a history of extensive timber exploitation in the late-19th and early 20th centuries. Most of the remaining, classic old-growth giant sequoia groves are now in protected status, but there are a variety of management challenges regarding forest restoration, fire management, and silviculture in this type on federal, state, and private lands.

These forests are characterized by the presence of giant sequoias dominating an upper canopy layer that is typically at heights of 45 to 75 m. Diameters at the base of mature "monarch" sequoias can reach 9 m or more, and 3- to 6-m diameter giant sequoias are relatively common in the variable sized groves (0.4 to 1600 ha). It is not feasible to sample the inner rings of the largest or oldest-appearing sequoias to determine their age, but the oldest trees that were felled during the logging era of late-19th century had pith dates from 1300 BC, which means they germinated and established about 3300 years ago!

A secondary canopy layer often exists in giant sequoia–mixed-conifer forests at about 30 to 55 m in height, and it is usually composed primarily of giant sequoia, sugar pine, and white fir, with occasional incense cedar and ponderosa pine or Jeffrey pine (*Pinus jeffreyi*) on drier sites, and red fir (*Abies magnifica*) at higher, cooler sites. From tree-ring studies of fire history and tree ages, it is evident that these forests sustained frequent, low-intensity surface fires for millennia, and the recruitment and mortality of sequoias and other tree species were profoundly influenced by this fire regime. Mean fire intervals in small areas (8–40 ha) ranged from as short as 2 to 3 years during the warmest and driest decades of the Medieval Warm (Drought) Period of about 900 to 1300 AD, to as long as 10 to 25 years during the coolest decades of the Little Ice Age (especially mid-1400s, early 1600s, and early 1800s). These variable fire frequencies persisted until about the 1860s, when large numbers of sheep were brought into the Sierras and the fine fuels (needles, forbs, and grasses) that carried the frequent surface fires were disrupted by grazing and livestock trails.

The frequent-fire regimes before the late-19th century maintained relatively open groves dominated by the sequoias and pine species. White fir and red fir, in particular, were maintained at relatively low densities in the groves because true fir seedlings and saplings were much more sensitive to fire-induced mortality than the sequoia and pine species. Frequent surface fires also limited the accumulation of downed woody debris (logs, branches, etc.) than was typical of other classic old-growth forests with very large trees—for example, the coastal Douglas-fir–hemlock forests of the Pacific Northwest.

Although high to moderate frequency and relatively low-severity surface fires were the norm in giant sequoia–mixed conifer forests for millennia, some fine-scale (small patch size) crown fire events probably also occurred at longer intervals. Small, relatively even-aged groups of sequoias tend to recruit in openings created by group or patch mortality events, some of which may have been caused by localized fire "torching" of individual trees or crowning fire behavior in small groups of trees. It is likely that these events involved mostly the understory pine and fir species and younger sequoias that occasionally established in relatively dense, small canopy groups. Sequoia germinates and establishes best on exposed mineral soil with abundant light, such as occurs following high-severity burning of small groups of trees. Occasionally, an apparently even-aged set of mature sequoias can be observed to grow in a nearly straight line for several hundred feet. Researchers speculate that this was formerly a linear canopy opening created by the fall of a monarch sequoia, followed by intense burning of the log and broken branches, producing a well-lighted, mineral soil seed bed.

A consequence of more than 100 years of fire suppression in giant sequoia–mixed-conifer forests was an extensive increase in the density of white fir within stands, and notable lack of seedlings and saplings of giant sequoias. Forest and fire ecologists and managers, concerned about these changes, were instrumental in leading to the 1963 report by the Leopold Committee. This report stimulated one of the earliest and most progressive prescribed burning programs in the nation at Sequoia and Kings Canyon national parks. Although this program has had a number of successes and setbacks, the amount of area treated or restored with the use of surface fires is relatively small, and far from what would be necessary to reintroduce fire at its historical levels.

Ponderosa Pine Forests of the Southwest

Key historical features were high-frequency, low-severity surface fires, and variable patterns of tree establishment, producing small-sized groups of relatively even-aged trees in multiple cohorts per stand.

The southwestern United States harbors the largest expanses of pure ponderosa pine forests in the world. A more-or-less continuous belt of ponderosa pine-dominant stands extend about 400 miles diagonally from northern Arizona southeastward across the Mogollon Rim to the Gila and Black Range Wildernesses in southwestern New Mexico. Additional extensive ponderosa pine belts are found in the numerous “sky island” mountains of the Southwest, and in the southern Rocky Mountain and Colorado Plateau extensions from southwestern Colorado into northern and central Arizona and New Mexico. Stands with ponderosa pine as the dominant species (>80% and sometimes 100% of the overstory trees) generally occur at elevations of about 1830 to 2130 m. Ponderosa pine mixes with pinyon pine (Colorado pinyon (*Pinus edulis*), single-leaf pinyon (*Pinus monophylla*), and Mexican pinyon (*Pinus cembroides*)), juniper species (*Juniperus* spp.), and various oak species (*Quercus* spp.) at the lower elevations. Ponderosa extends upward to 2600 m, and at the higher elevations, it grades into so-called mixed conifer, including various combinations of Douglas-fir, white fir, southwestern white pine (*Pinus strobiformis*), or limber pine (*Pinus flexilis*).

Ponderosa pine may the most fire loving of conifer species in the western United States. Some paleoecologists have speculated that its rapid expansion in the Southwest, beginning about 10 000 years ago, was related to development of dry spring and wet summer cycles, which may have promoted pine and grass vegetation, lightning, and especially fire. (We note, though, that ponderosa pine currently exists in the central Rocky Mountains where monsoonal summer rains are uncommon.) Numerous fire scar studies in the Southwest and elsewhere have clearly demonstrated the high frequencies of surface fires in ponderosa pine forests before the late 1800s, and a sudden drop in fire occurrence coinciding with livestock grazing and subsequent 20th century fire suppression activities by government agencies (Swetnam et al. 1999). Mean fire intervals were as low as 2–10 years across sample areas of about 8–100 ha (and occasionally much larger areas of 1200 or more ha). The shortest mean fire intervals (2–5 years) were typical of the grassy, productive stands on the Mogollon Rim in northern Arizona, and lower frequencies (every 6–10 years and up to 15 years) occurred in less extensive, lower-productivity stands in the sky islands of southern Arizona and New Mexico. Although frequent fires were the norm in the pre-European settlement era, occasionally 20-year or greater intervals occurred at stand scales of 1–15 ha during the 19th century. These occasional longer intervals were apparently quite important for ponderosa pine recruitment dynamics, because the establishment of trees over periods of several decades often coincided with the longest fire intervals (Brown and Wu 2005). The long fire intervals (gaps in fire occurrence) and years during which similar-aged pine tree “pulses” originated also tended to correspond with wetter and/or cooler climates, as indicated in reconstructions of rainfall amounts and drought indices using tree-ring width data.

Thus, earlier researchers’ general model of old-growth ponderosa pine characterized as uneven-aged stands composed of relatively even-aged groups is still valid (White 1985). However, we now understand that the small groups of even-aged trees (typically occupying 0.04–0.3 ha but as much as 0.8 ha) were often cohorts of trees established during several years or a decade or longer in favorable periods (i.e., fire gaps and/or wetter climate). Furthermore, there was some degree of synchrony of these cohort establishment events within and among ponderosa pine stands across the Southwest. Perhaps the most notable cohort events at these scales dated to the early 1800s (variable, but between about 1780 and 1830), 1910s to 1930, and the mid-1970s to 1980s. The last two regional cohorts (1910s to 1930, mid-1970s to 1980s) occurred during periods with a combination of much-reduced fire frequency (relative to the pre-European settlement era), much less intensive livestock grazing than had occurred from the 1880s to 1910s, and generally wetter and warmer periods that were favorable for seed production, germination, and establishment.

A consequence of 20th century changes in fire regimes and forest dynamics in southwestern ponderosa pine is the well-known fuel accumulation and crown fire problem. Fire ecologists and managers who are most familiar with this situation have concluded that uncharacteristic fuel accumulation and dense forest structure conditions that have developed in the past 100 years or more are now leading to extraordinary crown fire events. There remains some uncertainty and debate about the frequency and size distributions of crown fires in pre-European settlement southwestern ponderosa pine forests, but there are ample reasons to conclude that the sizes of the high-severity burn patches (total overstory mortality) in some recent crown fires in this type are outside the historical range of variation. There is a damaging synergy between the changes in fuels and forest structure as well as the extreme seasonal to multi-year droughts and earlier arrival of spring that have occurred since the late 1980s.

Old-growth trees are most abundant in the few forests that have remained unharvested for timber, but the effects of fire exclusion can alter forest structure even in the absence of tree cutting because populations of young trees expanded after fire exclusion and the removal of competing grasses. For example, never-harvested ponderosa forests on limestone soils on the North Rim of the Grand Canyon have maintained relatively open stands in places where at least a few large surface fires burned in the 20th century. Examples include the Powell Plateau and Fire Point (200–250 pines per hectare). In contrast, near Grandview Point on the South Rim, fires were completely excluded after 1887 and modern pine density exceeds 625 pines per hectare (Fulé et al. 2002). The Gus Pearson Natural Area, an unharvested forest on basalt soils near Flagstaff, Arizona, supported less than 65 pines per hectare at the end of the frequent-fire regime, but now has more than 3000 pines per hectare (Covington et al. 1997, Mast et al. 1999). These radical changes in tree density are typically associated with increased canopy fuels, decreased herbaceous production, and altered wildlife habitats, which underscores the point that, whereas the presence of old trees may be the defining factor of old growth, even stands with numerous old trees may have been altered in significant ways from the characteristics of the historic, frequently burned forest (Stephens and Fulé 2005).

Old-growth Ponderosa Pine–Douglas-fir Forests of the Colorado Front Range

Key historical features were mixed-severity fires and variable patterns of tree establishment, producing transient, moderate-sized patches, many with old trees first established after fires centuries ago.

Ponderosa pine is a major component of forests on the eastern slopes of the Colorado Front Range, generally between about 1675 and 2750 m in elevation. It is found intermixed with prairie grasses and shrublands at the lower ecotone, and with higher-elevation tree species toward the upper limits of the upper montane forests bordering on the subalpine zone (Lewis et al. 2005, Kaufmann et al. 2006). Ponderosa pine (a fire-resistant species) and Douglas-fir (a fire-sensitive species unless mature) are the dominant species in the lower montane zone (roughly 1830–2440 m in elevation). Historically, Douglas-fir was largely confined to north slopes at these elevations. Ponderosa pine forests in the Front Range are less productive than in many other areas, largely because of lower precipitation, with summer rainfall much less correlated with El Niño cycles than in the Southwest.

Lower overstory and understory productivity, and often a lack of continuous fine fuels to carry surface fires across large areas, historically resulted in less frequent fires than typically found in ponderosa pine forests elsewhere (Brown et al. 1999). Fuels accumulated during periods of 3–7 or more decades between fires, largely in the form of fuel ladders caused by gradual growth of smaller trees, shrubs, and combustible fuels beneath taller trees. Thus, periodic fires often killed patches of overstory trees (including old ones), thinned the overstory in other areas, burned as surface fires, or missed some areas altogether—classic features of a patchy, mixed-severity fire regime. It is likely that some stand-replacing fire occurred even in very sparsely forested patches dominated by shrub communities.

Colorado Front Range ponderosa pine forests typically were very patchy before the era of logging, grazing, and fire suppression. Patchiness stemmed from two processes: mixed-severity fire described above, and uneven tree recruitment into openings created by fire. Both processes made patch size and shape, tree ages and densities, and species composition transient over time. Patchiness was further shaped by local topography. Patch sizes varied, but generally were between 0.4 and 12 ha. Although mistletoe (*Arceuthobium* spp.) and insects, such as mountain pine beetle (*Dendroctonus ponderosae*), undoubtedly were present, there is no clear evidence they were effective disturbance agents affecting patch size and distribution beyond a local scale, at least at the lower elevations.

Old ponderosa pine trees were very common across historical landscapes in the Colorado Front Range, and a surprising number of old trees still exist after more than a century of human activities. In the unlogged ponderosa pine landscape at Cheesman Lake on the South Platte River (recently burned over and effectively destroyed during the Hayman Fire), trees more than 200 years of age (many more than 400) were found in considerably more than half of the patches (Huckaby et al. 2001). Reconstructions of historical conditions suggest that about 90% of this historical landscape had a canopy cover of 30% or less. Furthermore, openings or savannas, with up to 10% canopy cover provided by scattered (and often old) trees, constituted from 10% to 50% of the landscape, depending on fire severity and the timing of new tree establishment (M. Kaufmann, unpublished data). The transient, patchy openings or savannas often persisted for decades or even a century or more, and were a distinguishing feature of Front Range ponderosa pine landscapes.

Current landscape characteristics for ponderosa pine–Douglas-fir forests in the Colorado Front Range are not very different from those in the Southwest. Beginning about 1870, loggers removed a large portion of the old trees, initially creating more openings or open woodlands. Disturbance of the soil during logging and reduced competition from understory grasses and forbs during decades of heavy grazing apparently contributed to the establishment of large numbers of new seedlings. Then fire suppression removed the primary agent for keeping tree densities low, and the result was a fairly uniformly dense, young forest condition across extensive areas. These forests have almost no openings and are highly vulnerable to insect epidemics and uncharacteristically large crown fires. Thus, although historical differences existed in landscape conditions for the Southwest and Colorado Front Range, these differences were largely eliminated through human activities (Fig. 1). Nonetheless, very different requirements exist for restoration of old-growth conditions at a landscape scale in the Front Range, related primarily to differences in patch types and occurrence across the landscape.

Old-growth Ponderosa Pine, Jeffrey Pine, Jeffrey Pine–Mixed-conifer Forests of Eastern Washington, Oregon, California, and Northern Baja California

Key historical features were frequent low-severity fires and variable patterns of tree establishment, producing a fine-grain mosaic of small-sized patches, many with old trees.

Ponderosa pine and Jeffrey pine are the major tree species in the Eastern Cascades of Washington, Oregon, and California, the Modoc Plateau of northeastern California, the eastern Sierra Nevada, and portions of the Transverse and Peninsular Mountains of southern California and northern Baja California, Mexico. Elevations for this forest type vary from 900–2600 m across this broad geographic range. These forest types can be intermixed with pinyon–juniper woodlands and shrublands at the lower ecotone, and with moister, mixed-conifer forests or subalpine forests at the upper ecotone. Many of these forests are relatively dry with annual precipitations varying between 40–65 cm. Understory vegetation is a mixture of evergreen shrubs, grasses, and forbs. Grass cover is normally much less than in southwestern ponderosa pine forests, probably because of lower summer precipitation.

Forest productivity is lower than in ponderosa pine-dominated areas on the western side of the mountain ranges. The decrease in productivity on the eastern side is caused by rain shadows limiting precipitation from storms coming from the Pacific Ocean. Many of these forests do not contain a significant shade-tolerant tree species, although in some areas in the northern part of the range, Douglas-fir can increase in density if there is no disturbance. Some eastside forests in the central and southern portion of this range shift dominance from pine to white fir when disturbance is removed.

Frequent fire and limited precipitation maintained open forest structures. Fire return intervals varied from 10–25 years until the policy of fire suppression was initiated early in the 20th century. Western pine beetles (*Dendroctonus brevicomis*) and Jeffrey pine beetles (*D. jeffreyi*), along with several species of *Ips* beetles, killed relatively small patches of trees before these forests were changed by harvesting and fire suppression. The average size of historical regeneration patches in these forests has been estimated at 0.26 ha in the Warm Springs Reservation, Oregon (West 1969), 0.02–0.35 ha in

Pringle Falls, Oregon (Morrow 1985), and 0.01–0.07 ha in forests in northern Baja California, Mexico (Stephens and Fry 2005).

Jeffrey pine–mixed-conifer forests have been studied in the Sierra San Pedro Martir (SSPM), an isolated area located about 130 km southeast of Ensenada, Mexico. The SSPM is the southern terminus of the Peninsular Mountain Range that begins at the intersection between the San Bernardino and San Jacinto mountains in California (roughly 580 km separates the SSPM from the San Bernardino Mountains and the flora in these areas are very similar). The forests of the SSPM have experienced neither tree harvesting nor a policy of large-scale fire suppression. The Jeffrey pine-dominated forests in the SSPM are one of the very few that have not been significantly affected by management activities during the last 100 years and may serve to inform us about the effects of fire, insects, disease, and drought on a relevantly intact eastside ecosystem. We note, however, that livestock grazing since about 1950 may have begun to lengthen fire intervals and have other effects. The forests of the SSPM are not completely analogous to other eastside forests in the United States because past fire scars have been recorded primarily in early wood (Stephens et al. 2003) compared with the more common latewood or dormant ring boundary in the United States eastside forests. However, all of these eastside forests contain similar flora and fauna, and have similar physical environments.

High variability has characterized all live tree, regeneration, snag, and fuel attributes measured in the forests of the SSPM (Stephens 2004, Stephens and Gill 2005, Stephens and Fulé 2005, Stephens et al. 2007). The high variability in surface fuel loads would produce equally diverse fire behavior and effects, and this would maintain high spatial heterogeneity if the forest continues to burn under a frequent-fire regime. Examples of the high variation in forest structure are summarized from a systematic grid of plots that covered about 1235 ha. In this area, average diameter at breast height was 33 cm (range 2.5–112); average tree density was 23.6 trees per ha (range 5–52); and average basal area is 3.2 m^2 per ha (range 1–8). Average surface fuel loads were 2.6 metric tons per ha (range 0.004–28); total surface fuel load was less than the average load in 73% of the sampled area. Average snag density was 0.8 snags per ha (range 0–4.04), and 26% of sampled plots had no snags. Nearly half the area sampled (45.7%) had no coarse woody debris (CWD). Average CWD density, percent cover, volume, and weight were 17.6 pieces per ha, 1.5%, 7.7 m^3 per ha, and 2.84 metric tons per ha, respectively. Less than average values for CWD density, percent cover, volume, and weight were recorded in 57%, 64%, 67%, and 69% of the plots, respectively (Stephens et al. 2007). Average canopy cover was 26.8%, although canopy cover varied from 0–52%.

Most structural attributes measured in forests from the SSPM varied by about one order of magnitude even though the area sampled has similar aspects, slopes, soils, and dominant tree species. Similar variability probably occurred in many eastside forests in the United States before fire suppression and harvesting because they once experienced similar disturbance regimes and had comparable physical environments. High spatial variation in forest structure is a critical component of any restoration strategy concerning eastside, old-growth forests that once experienced frequent, low-severity fire regimes.

Old-growth Mixed-conifer Forests of the Northern and Central Rocky Mountains

Key historical features were relatively frequent low- to mixed-severity fires that produced a mosaic of small- to moderate-sized patches, many with old trees. Mixed-severity fires typically left an erratic pattern of mortality and recruitment on the landscape, something that is rarely observed today.

In the northern Rockies, mixed-severity fire regimes were found across a broad range of forest types, including some of those dominated by interior Douglas-fir and western larch (*Larix occidentalis*), western white pine (*Pinus monticola*), lodgepole pine (*Pinus contorta* subsp. *murrayana*), as well as some relatively moist ponderosa pine types (Arno et al. 2000). Mean fire return intervals varied from 25–40 years before livestock grazing and fire suppression altered natural fire regimes (Barrett 2004). Elevation ranges for this forest type are from 915–1980 m. In northern Rocky Mountain forests, mixed-severity regimes occupied about 50% of the area now in national forest lands; low-severity regimes included about 30% of this area, and stand-replacement regimes covered about 20% (Quigley et al. 1996).

Mixed-severity fire regimes produced highly diverse forest communities containing abundant seral, fire-dependent species, including multi-aged stands with large, old, fire-resistant trees that are of great importance as wildlife habitat (McClelland 1979). These regimes also helped produce intricate mosaics of even-aged tree groups and contrasting forest communities at the landscape level (Arno et al. 2000). Estimates of past patch sizes are rare.

Individual stands were often uneven-aged and multi-layered. Moderately short fire intervals allowed important shrubs and hardwoods to remain abundant. These included aspen, Scouler willow (*Salix scouleriana*), serviceberry (*Amelanchier* spp.), chokecherry (*Prunus virginiana*), and redstem (*Ceanothus sanguineus*) and evergreen ceanothus (*Ceanothus* spp.) (Arno et al. 1985). Small meadows and grassy openings and a variety of herbaceous plants would also have been abundant (Stickney 1990). As a result of the moderately frequent fires and variable fire severities, stands often formed a complex and intricate mosaic on the landscape.

On landscapes, such as large wilderness areas, the effects of fire exclusion tend to include greater uniformity in stand ages and in stand composition and structure, together with a declining diversity of undergrowth species (Arno et al. 2000). Basal area and numbers of trees per hectare may increase dramatically. This results in increased physiological stress and the opportunity for extensive forest mortality caused by epidemics of insects and diseases (Monnig and Byler 1992, Biondi 1996). Fire exclusion and related advancing succession also bring increased canopy densities and increased loads of dead and living (ladder) fuels across the forest landscape, which increases the likelihood of unusually severe and extensive wildfires.

Large stand-replacing fires have increased in recent decades, and modeling suggests that the effects of continued increases in forest density will be higher proportions of large stand-replacing fires (Keane et al. 1998). There will be a loss of multi-aged stands of seral tree species. The intricate, fine-grained landscape mosaic of diverse stand structures and compositions will be replaced by a coarser pattern of even-aged stands.

Under current conditions, a summer wildfire that escapes suppression could easily become a large, stand-replacing burn. Successional studies indicate that such a fire would probably give rise to new stands of lodgepole pine and Douglas-fir with little, if any, ponderosa pine (Arno et al. 1985). These post-fire stands would probably have a dense, even-aged structure, as well as abundant fire-killed downed trees, favoring continuance of a stand-replacement fire regime in the future (Scott 1998). Restoration of fire in mixed-severity regimes requires special care because fuel and stand structures in many areas are outside the historical range of variability (Quigley et al. 1996). Some naturally ignited fires burning under these altered conditions might adversely affect natural biodiversity (Harrington 1996).

SYNOPSIS

The case studies in the section above and features of old growth summarized earlier attest to the complexity of describing or defining old growth in frequent-fire forests of the western United States. Nonetheless, several features of fire-adapted, old-growth forests clearly distinguish them from old growth in other forest types in which fire is a very infrequent visitor. For example, periodic fire contributed to patchiness of the forest landscape, often working in concert with other small or moderate-sized natural disturbances, and with patch sizes governed by a host of variables. Regeneration was partly dependent on the creation of patchy openings, and then by the temporal and spatial coincidences of these openings with reduced fire frequency and favorable climate episodes for seed production, germination, and seedling survival. Fire assured that fire-sensitive tree species, such as Douglas-fir or white fir, generally failed to dominate landscapes, although they often were capable in the absence of fire of making forests vulnerable to uncharacteristically large and severe fire behavior. Patches varied in size and came with trees of many ages, accounting for the large numbers of old trees in the historical landscape, but also a shifting pattern of forest structure and composition over time.

Finally, all forest landscapes adapted to frequent fires suffered alike when subjected to logging, grazing, and fire suppression. They became highly vulnerable to uncharacteristic fire and damage caused by insects and drought. Now they require massive work to restore them to a healthy, sustainable condition. However, many of these forests still retain significant numbers of old trees, hidden from view by dense, younger trees and vulnerable to their competition. Carefully applied treatments often provide an opportunity to save these trees where they are in groups similar to pre-European settlement conditions, and, in the process, maintain old-growth conditions and begin to restore more natural levels of fire recurrence and surface fire behavior.

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